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APPLICATION OF THE FINITE ELEMENT METHOD TO CRACK EVALUATION OF WARSHIPS

M. Smith

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

Technical Memorandum

DREA TM 1999-154

September 1999

National Defence Défense nationale

Canada

National Defence Research and Development Branch

Défense nationale Bureau de recherche et développement

DREA TM 1999/154

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September 1999

TECHNICAL MEMORANDUM

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Abstract

The effects of artificial cracks in high stress components of the Halifax class frigate are investigated using two finite-element based methodologies currently being considered for use in the Improved Ship Structural Maintenance Management (ISSMM) project. In one method, static stress intensities are determined for each crack configuration using a one-percent exceedance wave load in sag. In the other method, the crack growth is predicted for a spectral wave loading corresponding to 100 hours in five metre head seas. A total of fifteen local models in the high stress region of the ship are investigated separately (three crack lengths for each of five locations). No evidence of uncontrolled crack growth is found using either of the two methods for any single crack configuration. The smallest margin of safety (ratio of fracture toughness to predicted stress intensity) is found to be 2.08. Crack growth rates are predicted for a 100-hour voyage in five metre head seas conditions. In this severe sea state the largest average crack growth rate is found to be 8.55 mm/hour, but at present this result has not been validated. Crack growth predictions can be extended to loadings of different magnitudes using the assumed linearity between wave height and response.

Résumé

On examine actuellement, dans le cadre du projet de Gestion améliorée de la maintenance de la structure des navires (GAMSN), les effets de fissures artificielles sur les composants subissant des contraintes élevées dans les frégates de la classe Halifax au moyen de deux méthodologies à éléments finis. Dans une des deux méthodes, on détermine l'intensité de la contrainte statique pour chaque configuration de fissures en utilisant une charge de vagues ayant un indice de dépassement d'un pour cent en creux. Dans l'autre méthode, la propagation des fissures est prévue pour une charge des vagues spectrale correspondant à 100 heures en mer contre une houle par l'avant de 5 mètres. Au total, quinze modèles locaux de la région du navire subissant une contrainte élevée sont étudiés séparément (longueurs de trois fissures pour chacun des cinq emplacements). Aucune des deux méthodes n'a permis de déceler une propagation démesurée des fissures pour une seule configuration de fissure. La marge de sécurité la plus faible (rapport de la résistance à l'intensité de contrainte prévue) est de 2,08. Les taux de propagations de fissures sont calculés en fonction d'un voyage de 100 heures dans une houle par l'avant de 5 mètres. Dans une mer d'une telle sévérité, la propagation des fissures moyenne la plus importante est de 8,55 mm/heure bien qu'à l'heure actuelle ce résultat n'a pas été validé. Il est possible d'extrapoler les prédictions de propagation de fissures aux charges des vagues de diverses amplitudes en utilisant la linéarité hypothétique entre la hauteur des vagues et la réaction.

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by
Malcolm J. Smith

Executive Summary

Background

A DRDB major project entitled Improved Ship Structural Maintenance Management (ISSMM) is currently underway to provide an efficient tool to aid in the assessment of the effect of various types of damage and degradation on the structural integrity and operational capability of Canadian Forces warships. Integral to this project is the use of rational, computer-based structural analysis methods, such as the finite element method, combined with realistic models of ship structure, loading, and damage.

The present study is an investigation of two methods for evaluating the effects of structural cracks on the local structural integrity and operational capability of warships. Both methods are based on a top-down finite element approach in which the response of a "global" model of a ship is used to create a realistic stress condition in a detailed "local" model that contains damage. The advantage of this general approach is that multiple damage scenarios, in the form of local models, can be investigated without having to re-calculate the response of the global model, hence reducing both the computational and the modelling effort required. The top-down approach is limited to damage scenarios not severe enough to affect the global response significantly.

In one method investigated in this study, the global response to an extreme wave load condition is used to obtain static stresses and stress intensities near crack damage in local models. This approach is conservative in that it uses a single, worst-case loading condition and does not provide the user with time-to-failure information. In the second method, the spectral response of the global model is obtained for given operational conditions and is used, in conjunction with experimental fracture mechanics laws, to predict the crack growth at any given location in the ship. The spectral method has yet to be proven effective in practice, but holds the promise of providing naval personnel with information directly relevant to maintenance planning and operating a ship in a damaged condition.

Principal Results

A total of fifteen local finite element (FE) models in the high stress region of the Halifax class frigate are investigated using both the static and the spectral top-down methods. Structural damage is represented by idealised cracks of three different lengths at each of the five locations modelled. For the static method, stress intensities are calculated for an eight-metre design wave load in sag, which is equivalent to a one-percent

exceedance load. For the spectral method, crack growth is predicted for a 100-hour duration in five metre head seas conditions. Two different ship speeds are investigated for comparison. No evidence of uncontrolled crack growth is found using either of the two methods. The largest stress intensities and crack growth rates are found to be located in the longitudinal bulkhead near of the junction of the main deck and the intakes. The smallest margin of safety (ratio of fracture toughness to predicted stress intensity) is found to be 2.08. Crack growth rates are predicted for a 100-hour voyage in five metre head seas conditions. In this severe sea state the largest average crack growth rate is found to be 8.55 mm/hour, but at present this result has not been validated.

Significance of Results

Static stress intensities are found to be consistent with crack growth rates predicted with the spectral method. In particular, locations of high stress intensity are also found to have high crack growth rates. The static method therefore appears to be useful for identifying crack configurations that will lead to large crack growth rates, but it is unable to provide time-to-failure information or allow the user to investigate the effects of different operational conditions. Static stress intensity predictions have been validated by comparison with analytical results for flat plates in a uniaxial membrane stress state.

Although the spectral wave loading method is computationally more expensive, it provides the user with information more directly useful for maintenance planning and structural failure avoidance. In particular, crack growth data collected for several different ship speeds and headings would provide guidance to naval personnel in selecting operational conditions in a damaged state. However, crack growth rates obtained with the spectral method have not yet been validated, either by experiment or by comparison with other numerical methods. The crack growth results presented in this study are therefore intended to demonstrate the capabilities of the spectral method rather than provide a definitive assessment of crack growth in the Halifax class warship.

Future Work

If the spectral method for evaluating crack growth is included as part of the integrated ISSMM software package, both the method and its implementation should be validated either numerically or experimentally. Some improvements will also be required in the automated re-meshing program to increase the software's flexibility and reliability. For a more complete set of crack growth results for the Halifax class frigate, additional locations and crack configurations would have to be investigated, and a full range of sea states used in the operational profiles. In some instances, much more detailed local models of structural components may be required to represent the crack propagation behaviour accurately.

1 Introduction

The Improved Ship Structural Maintenance Management (ISSMM) project was begun in 1996, following a three year planning period, with the objective of developing a set of rational, finite element based software tools for evaluating the structural integrity of ships in a damaged or degraded condition. This has now resulted in a comprehensive work plan for the primary software user interface to be used by naval personnel [1]. In addition, research-oriented software for top-down analysis has been developed and incorporated in the Maestro Graphics / Detailed Stress Analysis (MG/DSA) code [2]. MG/DSA is a user shell and graphical interface program for Maestro (Method for Analysis, Evaluation and STRuctural Optimisation [3]) currently being developed by Martec Limited with partial funding from DREA. Its principal function is to allow top-down structural analysis using the Maestro program. In addition, a top-down spectral analysis capability has been implemented in MG/DSA with interfaces to the 3D linear seakeeping code PRECAL [4], and the fatigue and fracture mechanics code LIFE3D [5]. These two top-down methodologies are used in the present study to evaluate the effects of cracks in high stress components of the Halifax class warship.

In the top-down approach, loading is applied to a relatively coarse "global" model, which may be a Maestro or VAST [6] finite element (FE) model of the ship. The response of the global model is then used to produce a realistic stress state, through prescribed boundary constraints, in detailed "local" models of the structural components containing damage. This avoids having to re-solve the global model for every structural component investigated. In this study, the top-down DSA method, which uses a Maestro global model and VAST local models, is used to evaluate static stress intensity factors for a number of high stress structural components in which cracks have been artificially introduced. In addition, the top-down spectral method, which uses VAST global and local models, is used to evaluate crack growth rates in an assumed sea state. The overall aim of this study is to show that the methodologies and software are able to make accurate assessments of the severity of structural damage, and that this information can be presented in a format useful to naval personnel.

The top-down methodologies are described in detail in Section 2. Test problems for validating the four-node fracture element are described in Section 3. The local models used in both the static and spectral loading methods are described in Section 4. Static stress intensities and margins of safety for the local models are given in Section 5, and crack growth rates for random wave loading are given in Section 6.

2 Methodology

Two approaches for evaluating the potential for crack growth in structural components are explored in the present study. One is to determine a static stress intensity factor K_I for a crack under a most probable extreme loading condition, and to compare this value with the critical stress intensity factor K_{IC} (fracture toughness) of the material. This approach is simplistic and conservative, and does not take into account amplitude variations in the loading. The other approach is to evaluate stress intensities under realistic low frequency spectral wave loading conditions. The resulting stress intensity spectra can then be used in conjunction with empirical crack growth laws to evaluate the crack growth for given operational conditions.

In both approaches, stress intensity factors in the vicinity of crack tips are determined using finite element analysis. The analysis performed may be static, using a static wave loading condition, or quasi-static in the case of low-frequency spectral wave loading. In both approaches, a top-down finite element methodology is used in which the response of the global model of the ship is coupled to refined models of high stress structural components. Stress intensity factors are obtained using a specially developed fracture element based on the VAST four-node quadrilateral shell [7]. The fracture element is provided with an additional node that may be associated with the crack tip. If this is done, stress intensities for the opening mode (mode I) and sliding mode (mode II) will be provided, in addition to the usual stress calculations.

2.1 Static Analysis of Stress Intensity Factors

The critical value of stress intensity K_{IC}, also called the fracture toughness, is the stress intensity under static loading beyond which uncontrolled crack growth occurs [8]. In the current study, stress intensities are calculated for several crack lengths and configurations using an eight-metre design wave load, which is equivalent to a load with a one-percent probability of exceedance. A margin of safety for any given crack can therefore be determined by simple comparison with the fracture toughness of the material.

The top-down analysis is performed using the MG/DSA software, with the Halifax class Maestro model for the entire ship structure (global model), and a refined DSA (VAST) model for the structural component containing the crack (local model). DSA models can be generated from elements of the Maestro model using the MG/DSA system, with provision for automatic prescribing of boundary displacements. The DSA model can be further refined in the immediate vicinity of the crack, either by manual refinement or by automated refinement with "smart" meshers. The latter are essentially template models of cracked plates that are embedded into an existing DSA model with multipoint constraints. With prescribed boundary displacements derived from the global model, the DSA model can be analysed as a standalone VAST run.

As was mentioned above, stress intensities are obtained by assigning the fifth node of fracture elements to the crack tip node. A group of fracture elements defined in this way act in common to give stress intensities for a crack tip region. The formulation is based on an added singular strain field derived from the analytical solution of a cracked plate in membrane deformation [7]. At the beginning of this study inconsistent results

were obtained for the stress intensity factors using this element. As a result, changes were required in the element formulation, and a validation study on a number of simple examples with analytical results was subsequently performed. Some of the results of the validation study are given in the Section 3. Examples of stress intensities obtained for high stress regions of the Halifax class frigate are given in Section 5.

2.2 Spectral Analysis of Crack Growth

Crack growth rates under spectral wave loading conditions can be determined using the top-down methodology described in detail in Reference [9]. The procedure is illustrated in Figure 2.1, and has recently been incorporated into the LIFE3D fatigue code as part of the ISSMM project [10]. Spectral wave loading is achieved by combining unit-height regular wave Response Amplitude Operators (RAOs) calculated using the seakeeping code PRECAL with an appropriate spectral model of sea state and operational profile for a typical voyage. In doing so, it is assumed that the RAOs scale linearly with wave height. The regular wave RAOs and spectral wave model together define a range of possible load cells in which the ship will operate. The operational profile defines the probability of occurrence of each load cell, and hence the number of load cycles in each cell.

The response of the ship to spectral wave loading is determined using a quasi-static approach. Loading is applied in the form of PRECAL RAOs, i.e., panel pressure distributions and rigid body accelerations corresponding to unit-height regular wave loading. The RAOs are applied statically to the global model, and its response is in turn transmitted to the local model through prescribed boundary deformations. If applied directly, this procedure would be computationally expensive, since the global response would have to be calculated for each load cell and frequency in the operational profile. Instead, the global response is pre-calculated for static unit-pressure loading at the panel locations, and static unit-acceleration loading of the global model as a whole. This allows transfer functions to be assembled that relate the stress intensity at a given crack tip to the panel pressures and ship motions. In the spectral method, these static transfer functions are combined with the RAOs to produce quasi-static response values in the load cells.

The ISSMM software incorporated in MG/DSA provides a PRECAL interface that enables unit-pressure and unit-acceleration load cases to be automatically identified in the VAST global model. Because these loads are static, artificial constraints must be imposed on the global model. The global responses for all the load cases are stored on file, and are subsequently used to impose prescribed boundary constraints on each of the local models. A local analysis is then performed in which stress intensity factors are obtained for every unit-load case. Combination of these results with the RAOs gives a direct relationship between wave loading and the stress intensity at a given crack tip.

Combining these transfer functions with the sea state defined in the operational profile allows spectra of stress intensity to be calculated. The spectra are functions of the encounter frequency, i.e., the frequency of wave loading as seen from the reference frame of the moving ship. The LIFE3D program uses these spectra to calculate crack growth rates based on empirically derived formulas such as the Paris law.

The whole process described above is conducted iteratively at equally spaced time intervals. The following steps are performed in each iteration:

(i) the stress intensity spectrum is calculated;
(ii) the elongation of the crack is determined based on the crack growth rate and the interval time;
(iii) the local model is re-meshed (using VGCON) for the updated crack length; and
(iv) the local model is re-analysed (using VAST) to update the stress intensity spectra.

The local model should have in the vicinity of the crack a refined rectilinear mesh of fracture elements with sufficient room for the crack to grow, if the automated re-meshing is to be carried out successfully.

For the Halifax class frigate, a 200 panel PRECAL model is used to obtain pressure RAOs and to generate unit pressure load cases. With six additional unit-acceleration load cases and a still-water load case, a total of 207 load cases and response vectors are calculated for the global model. A Bretschneider spectral wave model is used with unidirectional properties. Simple operational profiles are based on a ship travelling in five metre head seas with a total operational time of 100 hours. The effects of two different ship speeds on the crack growth are examined in Section 6.

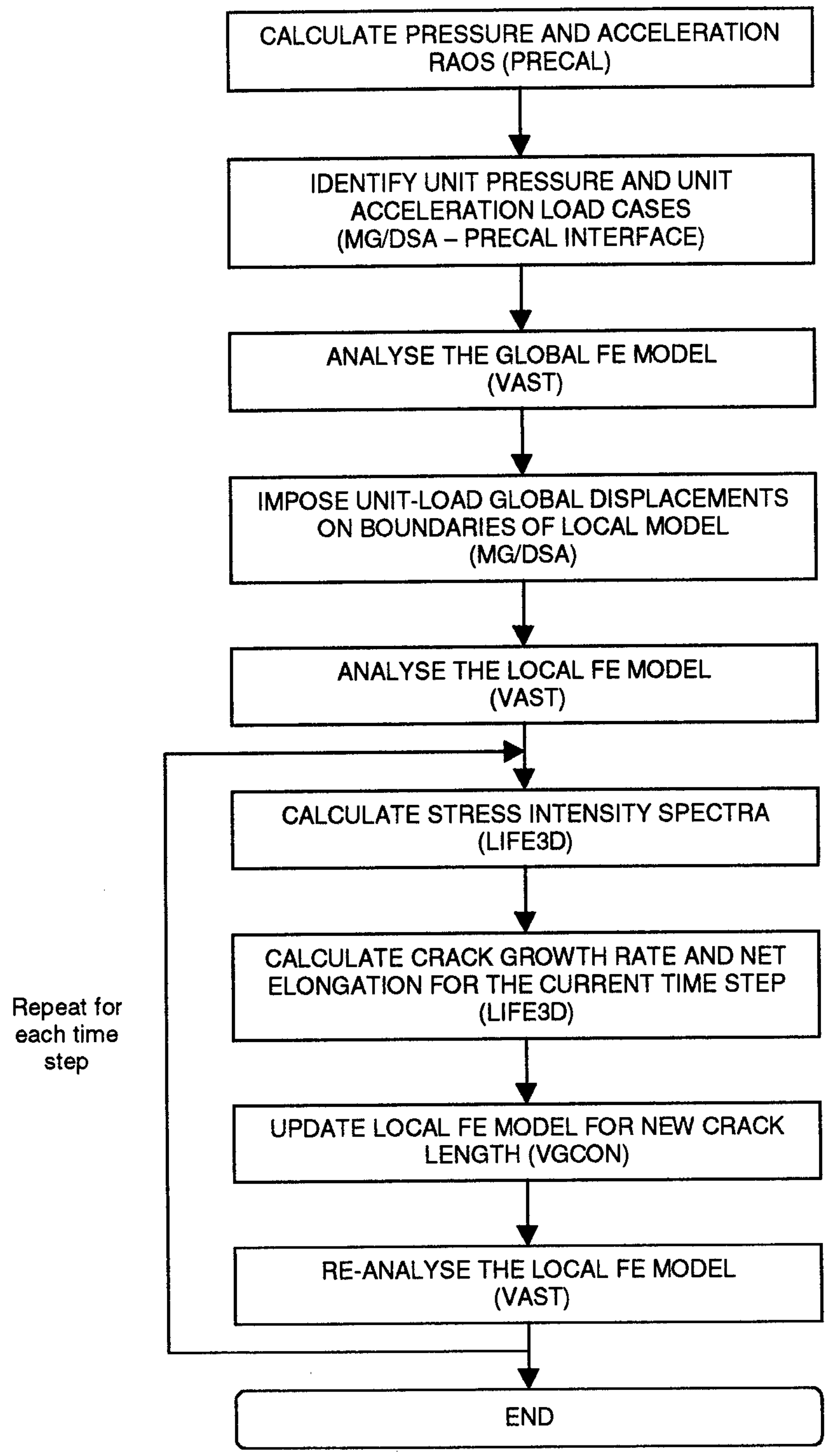


Figure 2.1: Spectral Analysis of Crack Growth Using Top-Down Method

3 Validation of the Five-Node Fracture Element

A five-node fracture element was implemented in VAST during an earlier phase of the ISSMM project as a replacement for a thirteen-node membrane element [7]. It is based on the VAST four-node quadrilateral shell element, and allows singular stress fields to be included through assigning the fifth node to a crack tip. The five-node element is generally preferable to the thirteen-node element as it facilitates meshing with other quadrilateral and triangular shell elements. Also, unlike the earlier element, the crack tip node does not have to be one of the element corner nodes. Instead, it can be associated with any node in the model, thus removing any restriction as to which elements can be included in the stress intensity calculation. At the beginning of the present study, poor stress intensity results were obtained with this element in almost every case that was tested. Following changes to the element formulation, better results were obtained. This section presents some validated stress intensity results using the corrected element.

First, a flat plate with an edge crack (Figure 3.1) was analysed for uniform loading of 100 MPa in the direction perpendicular to the crack. The VAST result for the mode I stress intensity factor was 71.9 MPa√m, or about 8% larger that the analytical result of 66.3 MPa√m. The problem was analysed again after the plate was rotated about x-axis a small amount (Figure 3.2). The stress intensity factor was 71.4 MPa√m. Before corrections were made to the element, the stress intensities were very sensitive to plate orientations. Figure 3.3 shows the stress intensity for a central crack in a 100 MPa stress field. The stress intensity was 1370 MPa√mm as compared to the analytical value of 1260 MPa√mm. The discrepancies between analytical and FE results are mainly due to the coarseness of the mesh used in the region of the crack tips.

A third example illustrates the situation for non-planar structures. The cylinder in Figure 3.3 is in uniaxial tension and has a 62mm circumferential crack. The predicted stress intensities at the two ends were 1088 MPa√mm, or about 10% larger than the analytical value of 990 MPa√mm, which applies to a flat plate with a centre crack of the same length and a plate width equal to the circumference of the cylinder. This example shows that although the element stress intensity formulation is based on a membrane stress state in a flat plate, the FE model in which it is used need not be a flat surface. Moreover, a crack does not have to be perfectly straight, but rather can be comprised of a number of straight segments. This is important when modelling cracks near intersections of plating and stiffeners, as direction changes can easily occur there.

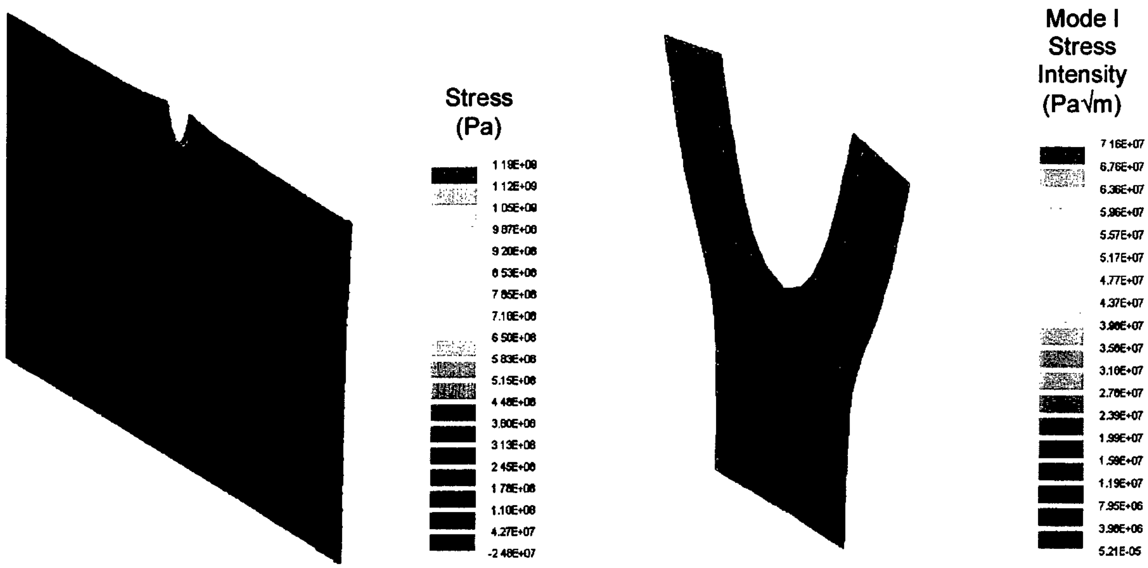


Figure 3.1: Edge crack model in uniaxial stress. Opening mode stress intensity at the deformed crack tip (right).

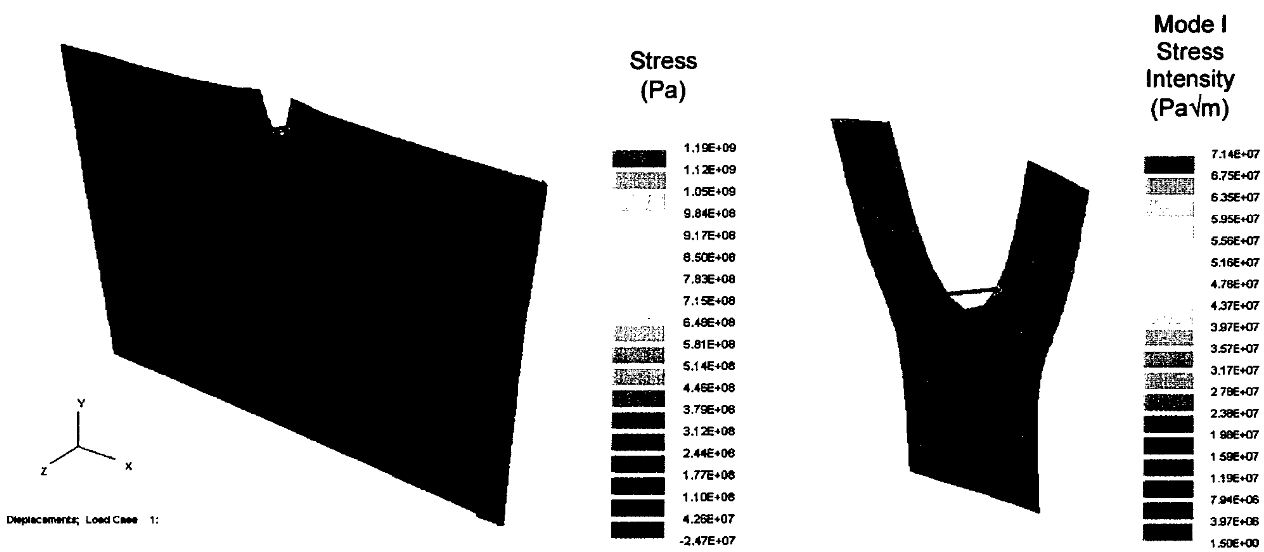


Figure 3.2: Edge crack model rotated about x-axis. Opening mode stress intensity at the deformed crack tip (right).

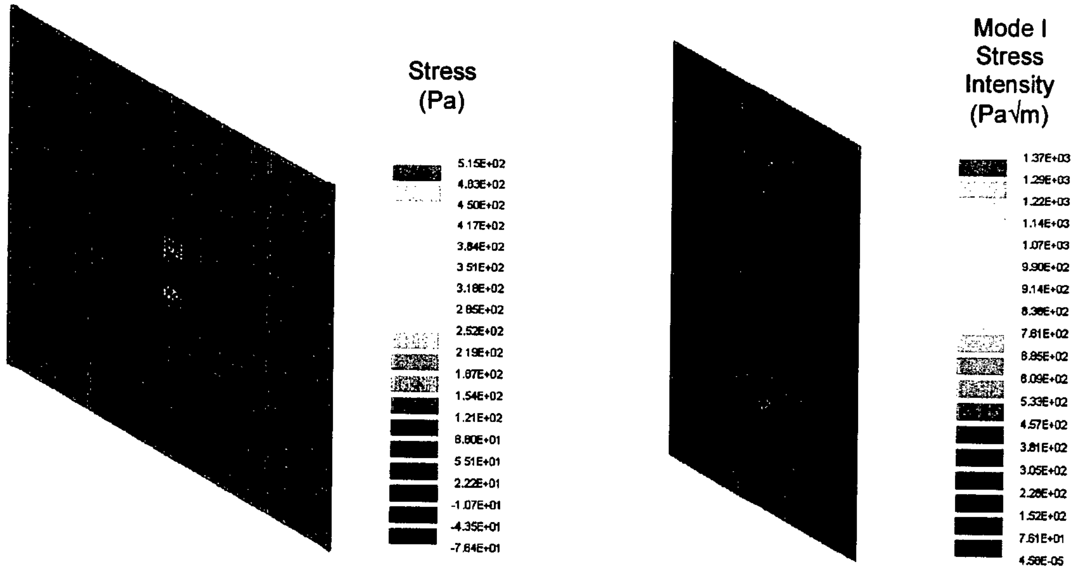


Figure 3.3: Centre crack model in uniaxial stress. Opening mode stress intensity at crack tip (right).

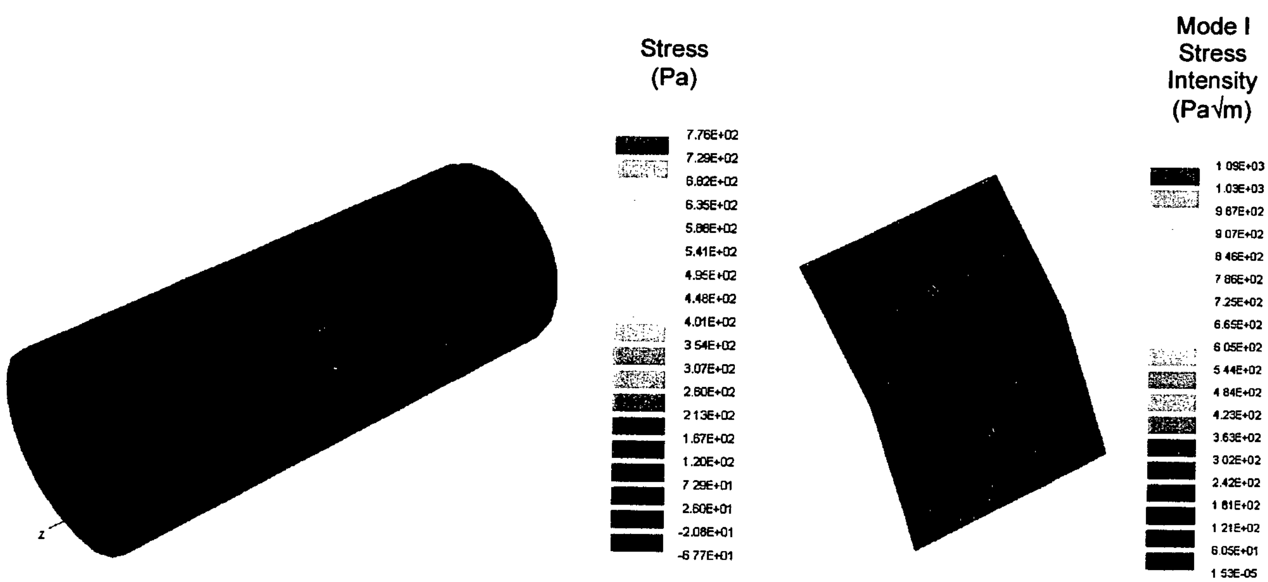


Figure 3.4: Cylinder model in uniaxial stress. Opening mode stress intensities at crack tips (right).

4 Crack Models

Previous analysis of the Halifax class frigate with Maestro has indicated that maximum stresses in hull-girder bending occur near midships, at the junction of the intakes and the main deck. Fifteen different local models were created at the five locations shown in Figure 4.1. At each of the five locations, straight cracks of three different lengths (100mm, 500mm, and 1000mm) were introduced. Examples from each location are shown in Figures 4.2-4.6. A complete list of local models is given in Table 4.1.

Figure 4.2 shows a crack extending toward the ship centreline, just aft of the intakes, in the high strength portion of the deck. The crack runs perpendicular to longitudinal stiffeners spaced at intervals of 825mm. In the three models at this location, the stiffeners are modelled with beam elements. The plate is modelled with four-node shell elements (yellow), except in the region of the crack where four node fracture elements are used (orange). If the crack is long enough to intersect a longitudinal stiffener, the beam elements are actually severed at the intersection point. This has the effect of exaggerating the weakness of the deck, and is therefore conservative.

Figure 4.3 shows a crack in the main deck to the port side of the intake structure, running along the junction of the deck and the frame in the transverse direction leading away from the superstructure. The crack runs perpendicular to longitudinal stiffeners spaced at intervals of 550mm. For the 100mm and 500mm crack length models at this location, the decks, girders and stiffeners are all meshed with shell elements. For the 1000mm crack length model, the longitudinal stiffeners and transverse frames were modelled as beam elements. The longitudinal stiffeners remained intact at the intersection with the crack, and the crack continues in a straight line.

The longitudinal bulkhead model (Figure 4.4) consists of a plate panel with beam stiffeners running parallel to the crack. The panel is 5mm thick, except in a 575mm wide strip across the top (nearest the crack opening) where it is 10mm thick.

The side shell model (Figure 4.5) is a flat panel with beam stiffeners spaced at 400mm running perpendicular to the crack. The top half of the panel is 12mm thick; the bottom half is 10mm thick. As with the high strength steel deck model, stiffeners are severed at the intersections with the crack. The uptake side panel model (Figure 4.6) was selected because Maestro static response results indicated high shear stresses in this component. It is relatively thin (4mm) with beam stiffeners running parallel to the crack.

For all the models used in this study, the refined mesh around the crack was created manually, i.e., without the use of smart meshes. This is because the automated re-meshing of the crack was found not to work correctly when smart meshes were used. In particular, the multipoint constraints used to tie the smart mesh to the rest of the local model were not properly maintained during the re-meshing. This aspect of the software will be corrected so as to enhance its flexibility.

Table 4.1: Halifax Class Local Models		
Case	Component	Crack Length (mm)
1	Inner Main Deck (A517)	100
2	Inner Main Deck (A517)	500
3	Inner Main Deck (A517)	1000
4	Outer Main Deck (350WT)	100
5	Outer Main Deck (350WT)	500
6	Outer Main Deck (350WT)	1000
7	Longitudinal Bulkhead	100
8	Longitudinal Bulkhead	500
9	Longitudinal Bulkhead	1000
10	Side Shell	100
11	Side Shell	500
12	Side Shell	1000
13	Uptake	100
14	Uptake	500
15	Uptake	1000

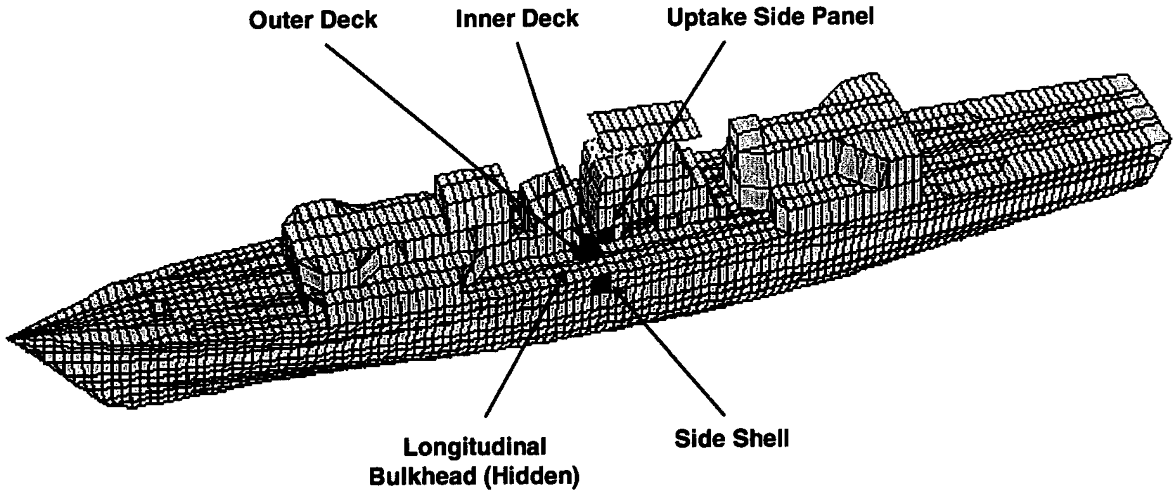


Figure 4.1: Maestro Model of the Halifax Class Frigate Showing the Five Locations of the Local FE Models.

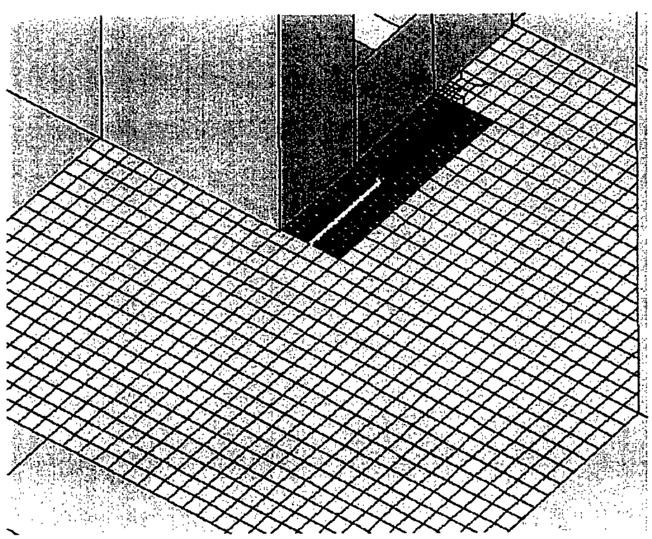


Figure 4.2: Inner Main Deck, 500 mm Crack (Case 2).

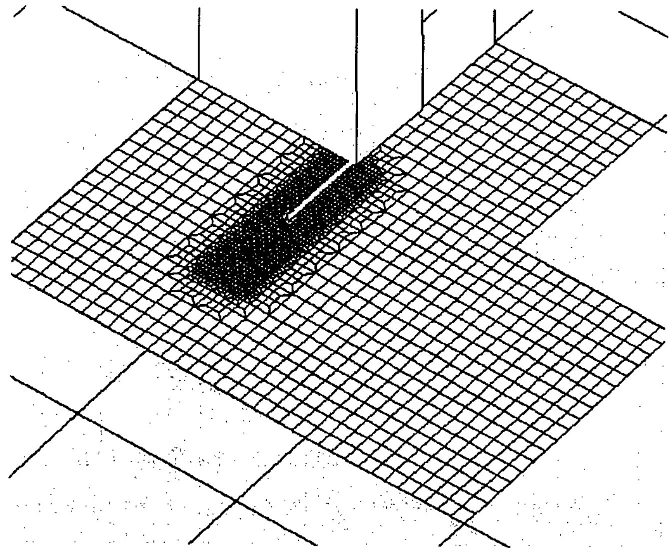


Figure 4.3: Outer Main Deck, 500mm Crack (Case 5).

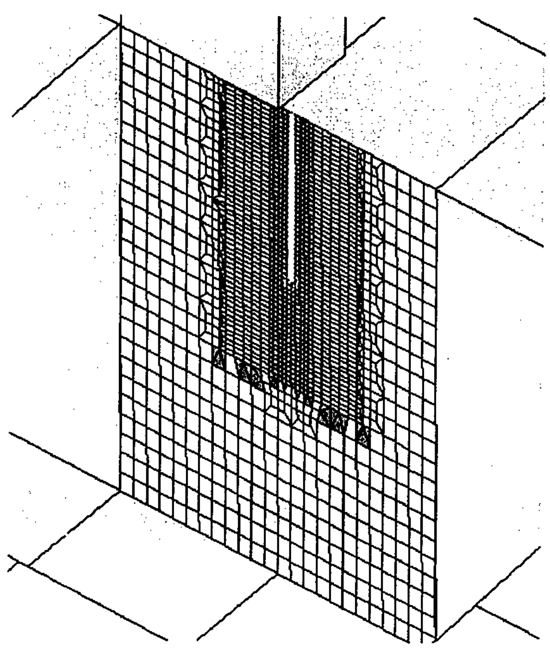


Figure 4.4: Longitudinal Bulkhead, 1000mm Crack (Case 9).

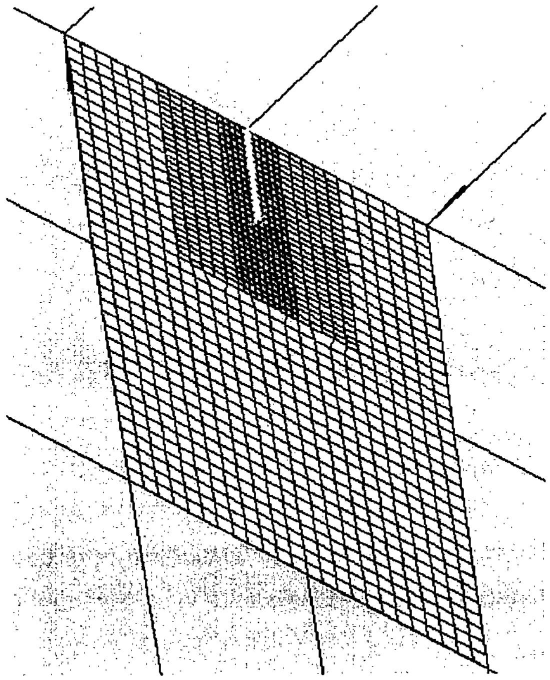


Figure 4.5: Port Side Shell, 500mm Crack (Case 11).

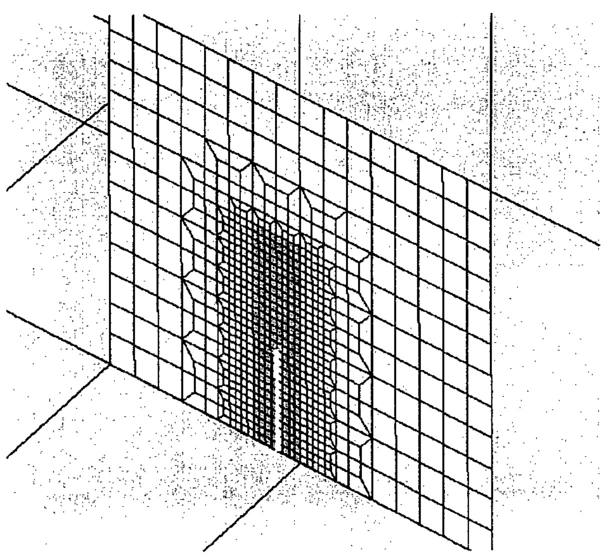


Figure 4.6: Uptake Side Panel, 500mm Crack (Case 14).

5 Stress Intensities Under Static Loading

Figures 5.1 – 5.15 show the stress and stress intensity fields predicted for three crack lengths at the five crack locations described in the previous section. Stresses shown in these plots are maximum principal values and stress intensities are for mode I, except where noted. Results were computed using an eight-metre design wave load in sag. The margin of safety (S) is given in Table 5.2 for each case, where the S is defined as

$$S = \frac{K_{IC}}{|K_I|} = \frac{\text{fracture toughness}}{\text{predicted stress intensity}}$$

Fracture toughness values for 350WT and A517 were calculated using experimental values obtained from Reference [11]. The lower values of the ranges in Table 5.1 were used to obtain conservative S estimates.

None of the models tested indicate a possibility for uncontrolled crack growth. Of the five locations, the largest stress intensities were found in the longitudinal bulkhead (Case 9) and the outer main deck (Case 6). Large values in the longitudinal bulkhead are primarily due to its comparatively small thickness of 5mm. Mode II stress intensities were found to be negligible at all locations except the uptake side panel, where large values for the sliding mode were obtained due to high shear stress in this component (see Figure 5.13-15).

In most instances, stress intensities increase with crack length, as is predicted by analytical expressions for uniaxial stress states. Both the inner main deck and uptake models show a decrease in the stress intensity at a crack length of 1000mm because the cracks propagate into lower stress regions. The drop is most apparent for the inner main deck, where there is a large stress gradient in the transverse direction. Here, as the crack lengthens, the stress initially becomes less compressive and so the magnitude of the stress intensity falls. At a length of 1000mm the stress intensity has fallen to a level where the crack will no longer propagate, as will be seen in Section 6.

Table 5.1: Fracture Toughness	
Material	K_{IC} MPa√mm
350WT	8550 - 9445
A517	7598 - 8942

Table 5.2: Static Stress Intensities and Margins of Safety for Sag Loading				
Case	Component	Crack Length (mm)	K_I MPa$\sqrt{mm}$	S
1	Inner Main Deck (A517)	100	-1760	4.32
2	Inner Main Deck (A517)	500	-1990	3.82
3	Inner Main Deck (A517)	1000	-445	17.1
4	Outer Main Deck (350WT)	100	-1120	7.59
5	Outer Main Deck (350WT)	500	-2270	3.77
6	Outer Main Deck (350WT)	1000	-3900	2.18
7	Longitudinal Bulkhead	100	-1990	4.27
8	Longitudinal Bulkhead	500	-3630	2.36
9	Longitudinal Bulkhead	1000	-4080	2.08
10	Side Shell	100	-1270	6.73
11	Side Shell	500	-2630	3.25
12	Side Shell	1000	-2910	2.94
13	Uptake	100	-1740	4.91
14	Uptake	500	-3400	2.51
15	Uptake	1000	-2770	3.10

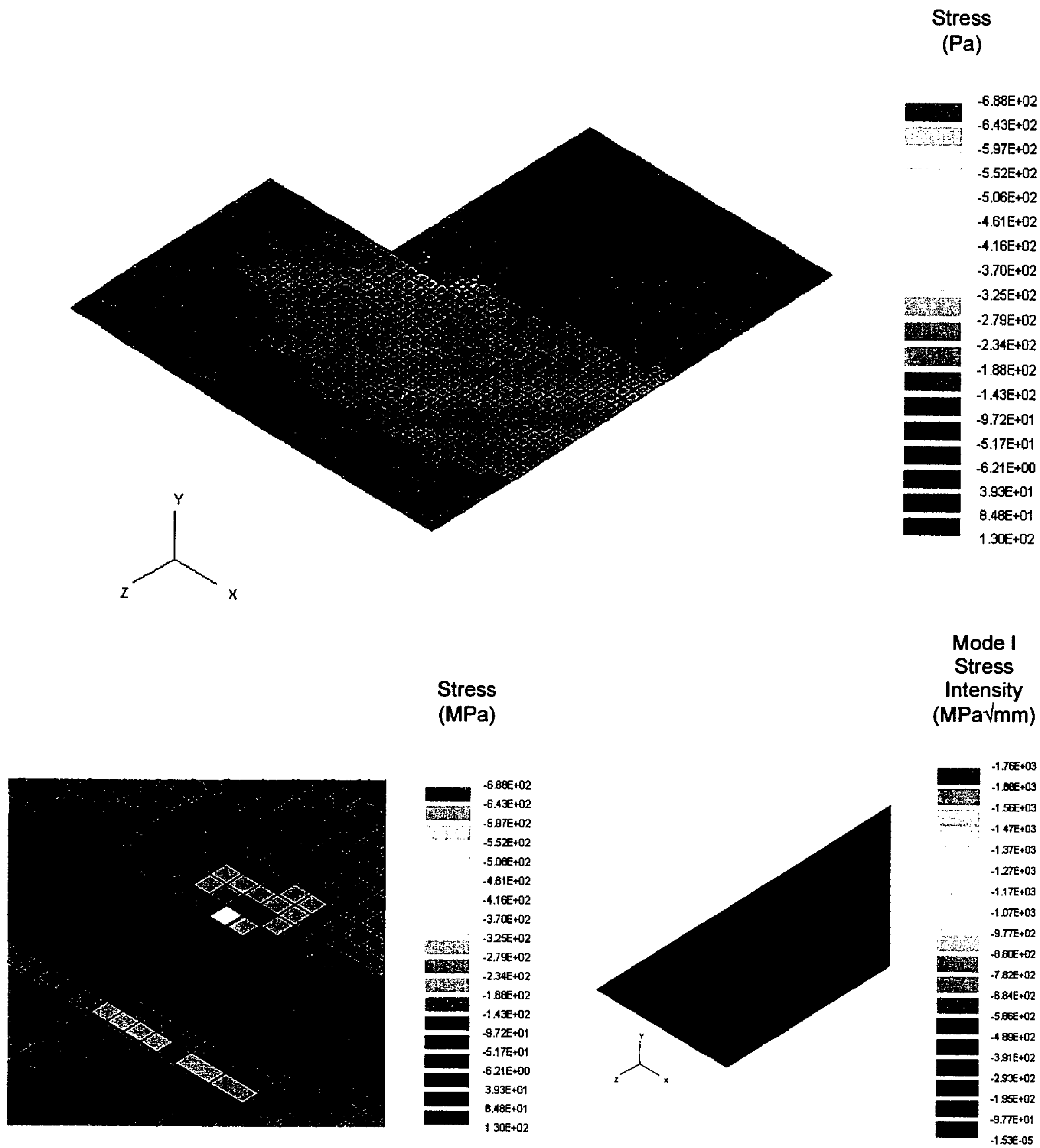


Figure 5.1: Stress Field (top and left) and Stress Intensities (bottom right) for the Inner Deck Model with a 100mm Crack in High Strength (A517) Material (Case 1).

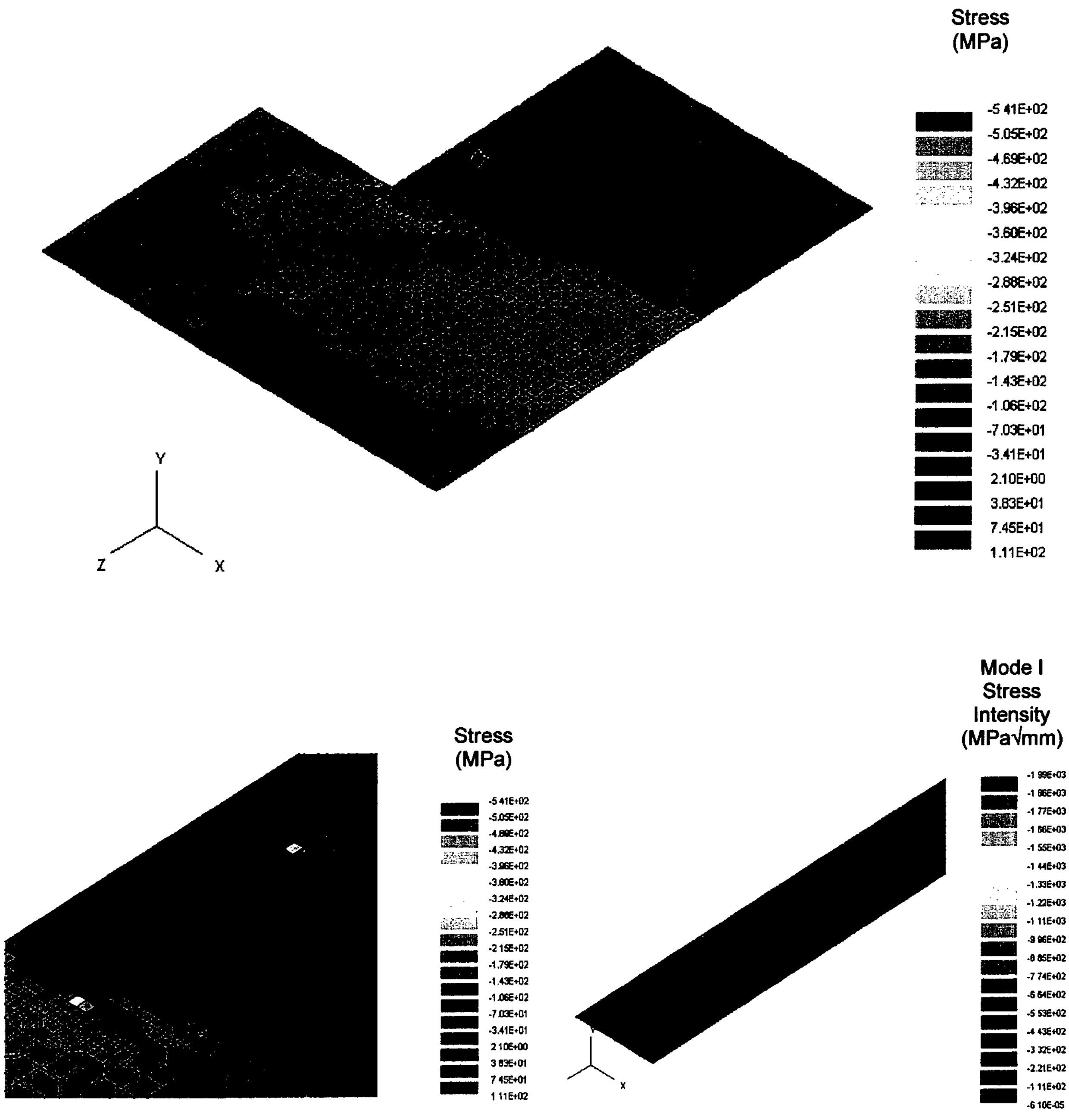


Figure 5.2: Stress (top and left) and Stress Intensities (bottom right) for the Inner Deck Model with a 500mm Crack in High Strength (A517) Material (Case 2).

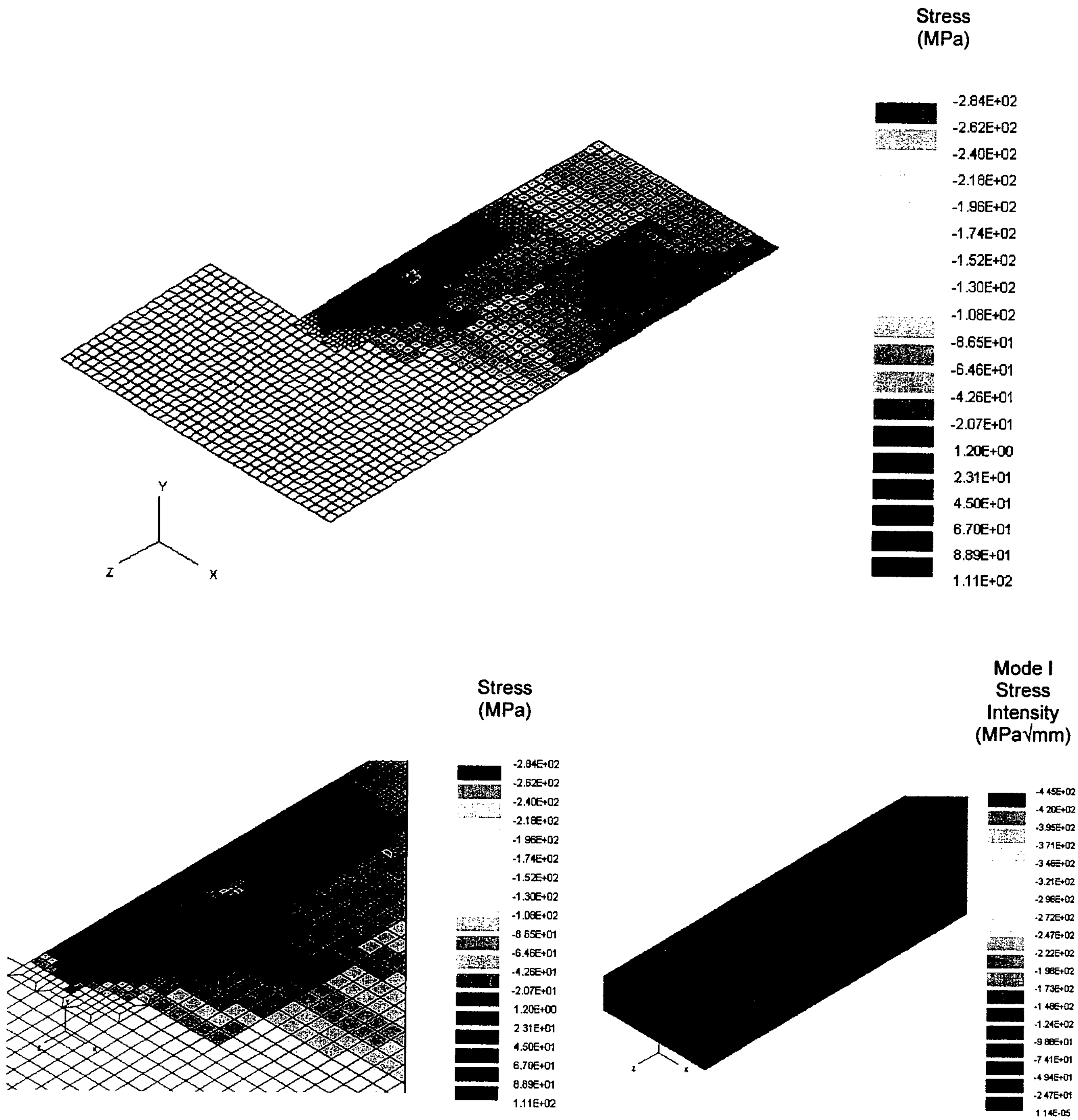


Figure 5.3: Stress Field (top and left) and Stress Intensities (bottom right) for the Inner Deck Model with a 1000mm Crack in High Strength (A517) Material (Case 3).

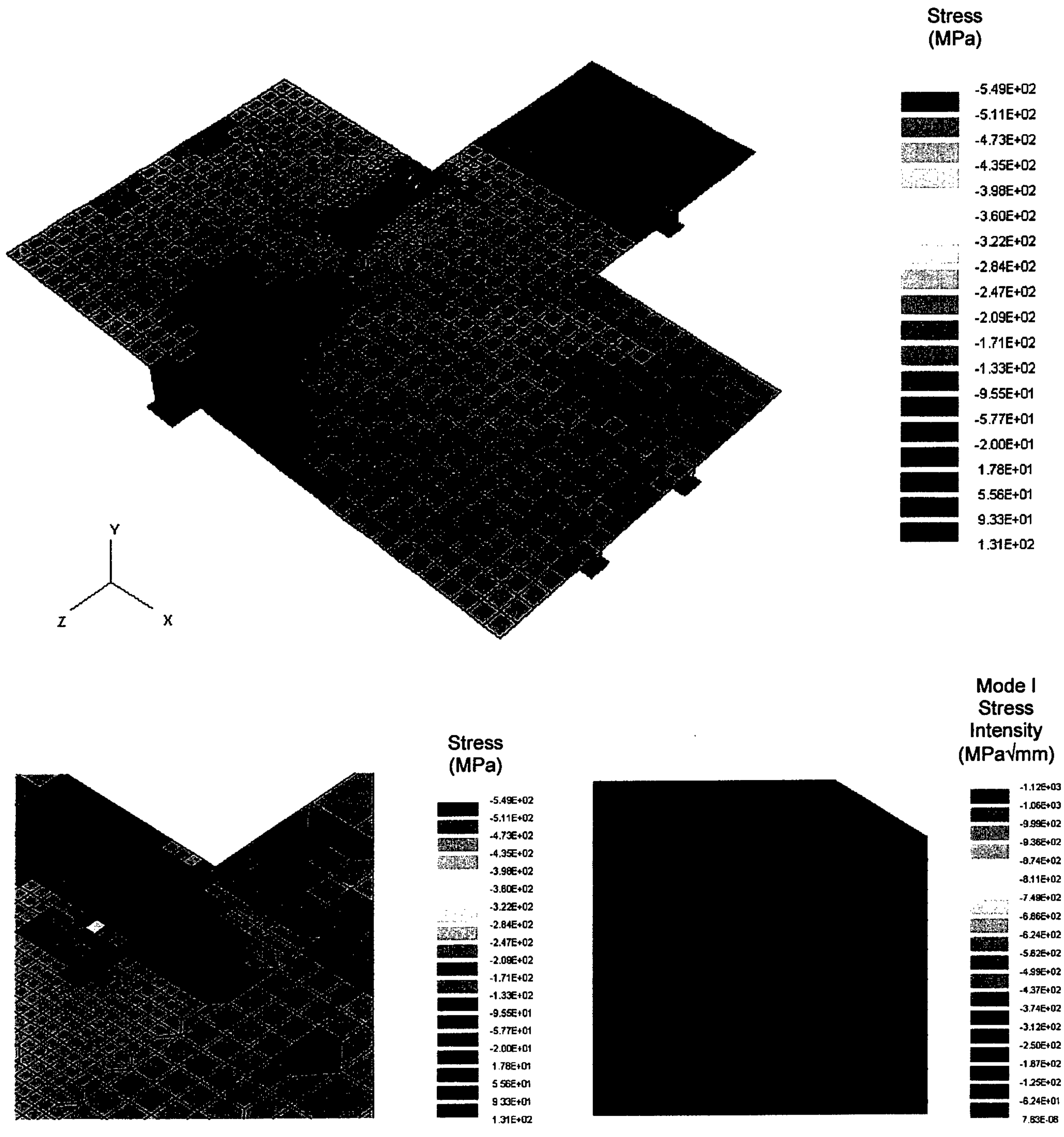


Figure 5.4: Stress Field (top and left) and Stress Intensities (bottom right) for the Outer Deck Model with a 100mm Crack in 350WT Material (Case 4).

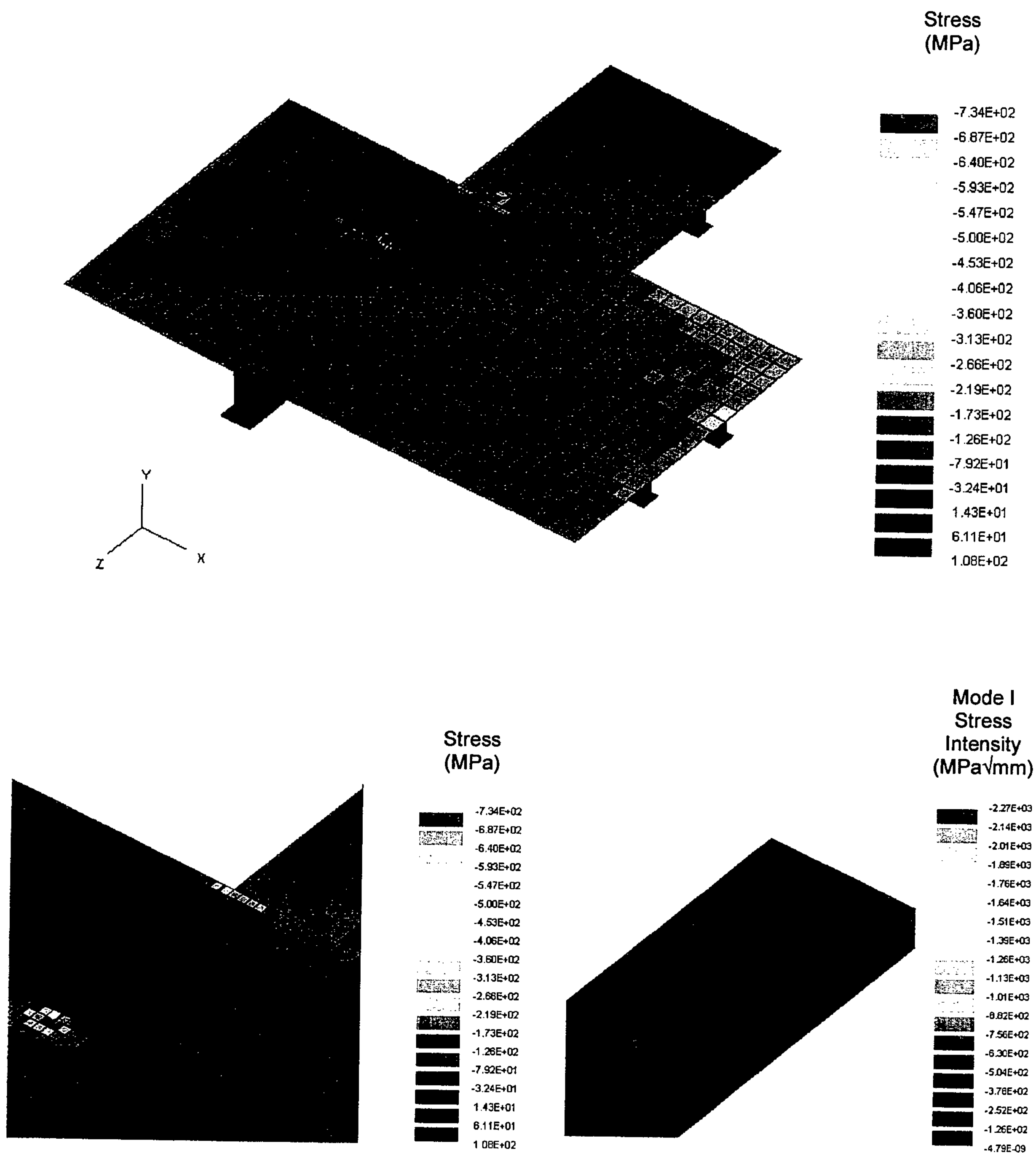


Figure 5.5: Stress Field (top and left) and Stress Intensities (bottom right) for the Outer Deck Model with a 500mm Crack in 350WT Material (Case 5).

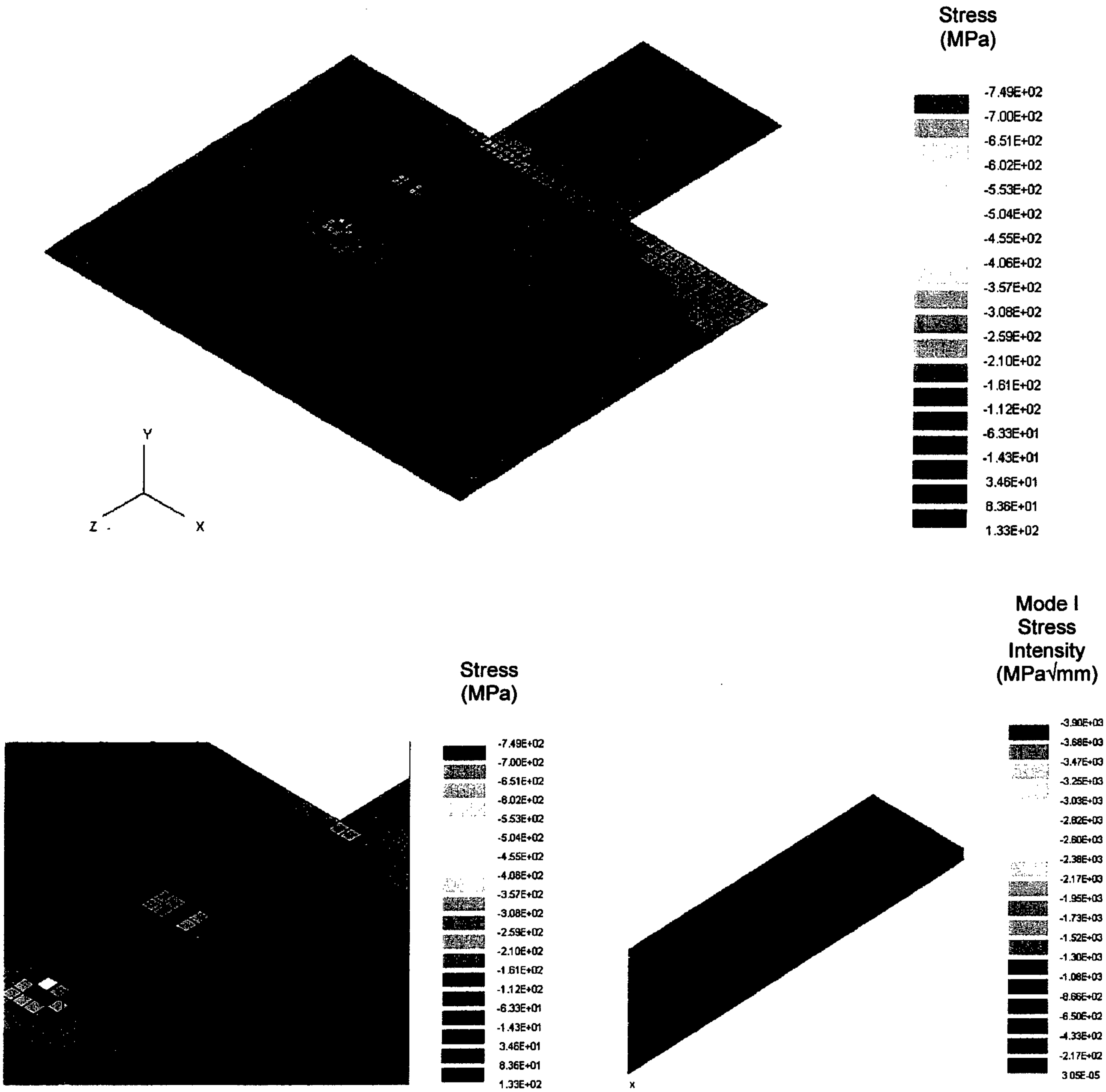


Figure 5.6: Stress Field (top and left) and Stress Intensities (bottom right) for the Outer Deck Model with a 1000mm Crack in 350WT Material (Case 6).

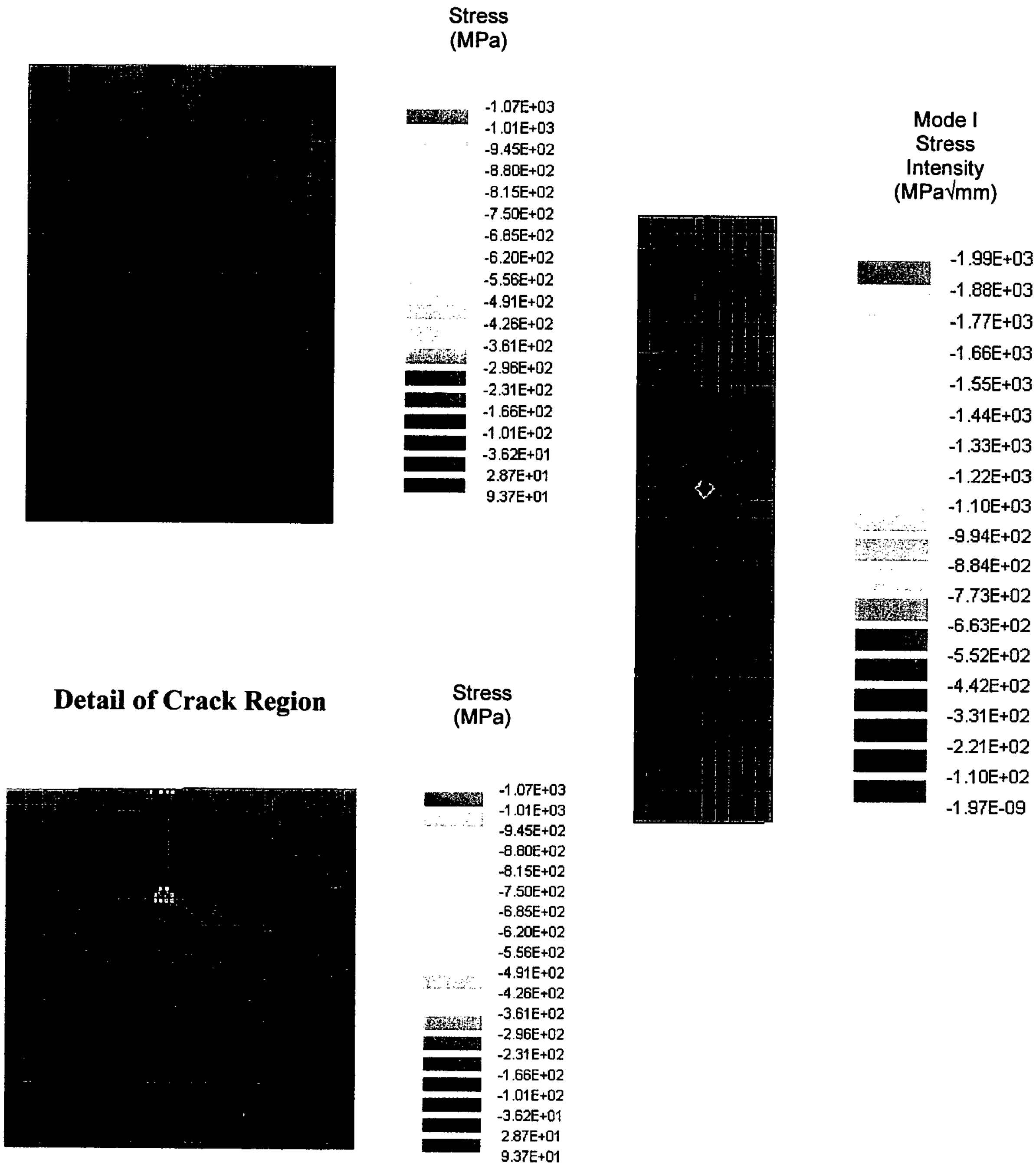


Figure 5.7: Stress Field (left) and Stress Intensities (right) for the Longitudinal Bulkhead with a 100mm crack (Case 7).

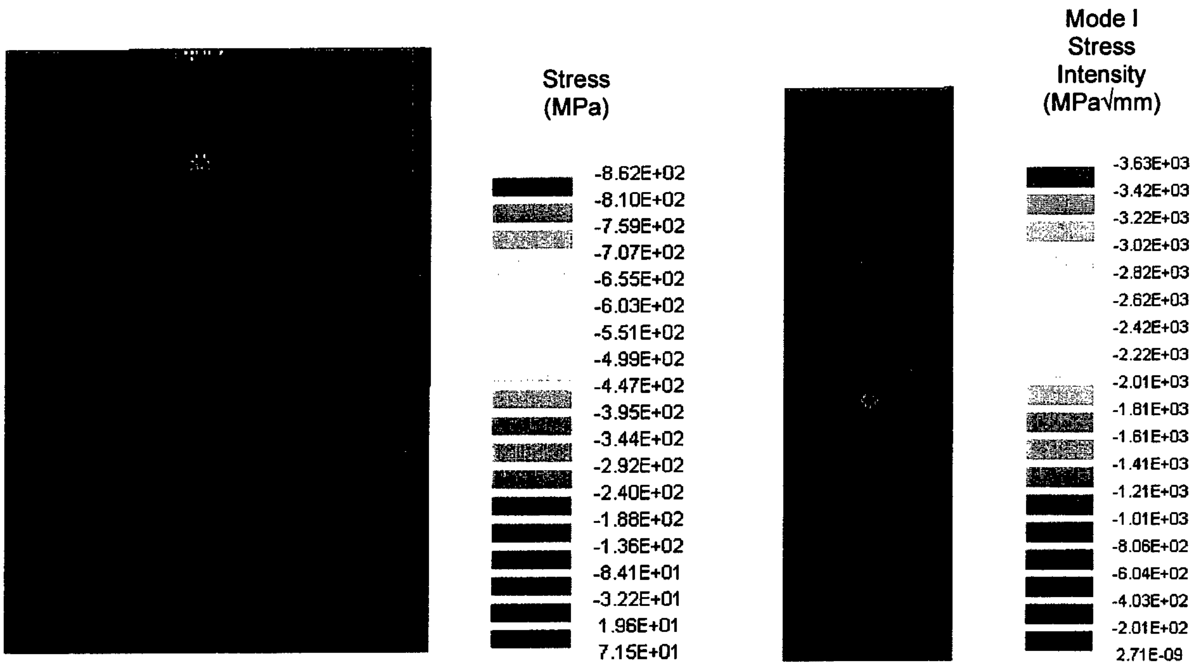


Figure 5.8: Maximum Stress Field (left) and Stress Intensities (right) for the Longitudinal Bulkhead with 500mm crack (Case 8).

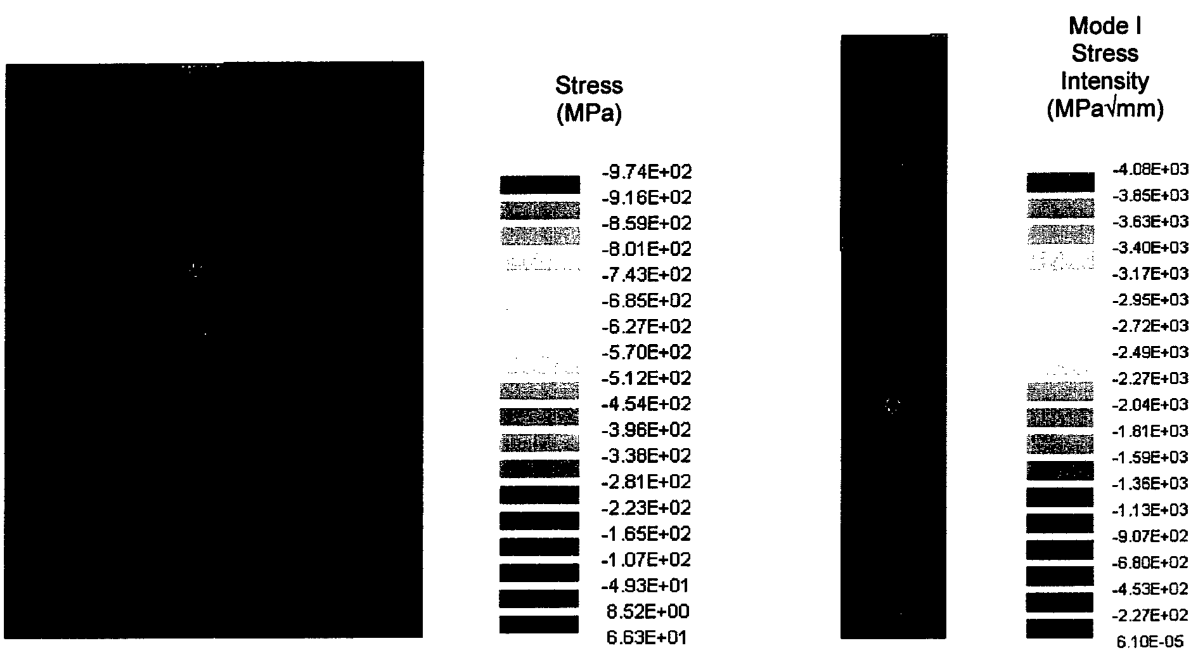


Figure 5.9 Maximum Stress Field (left) and Stress Intensities (right) for the Longitudinal Bulkhead with 1000mm crack (Case 9).

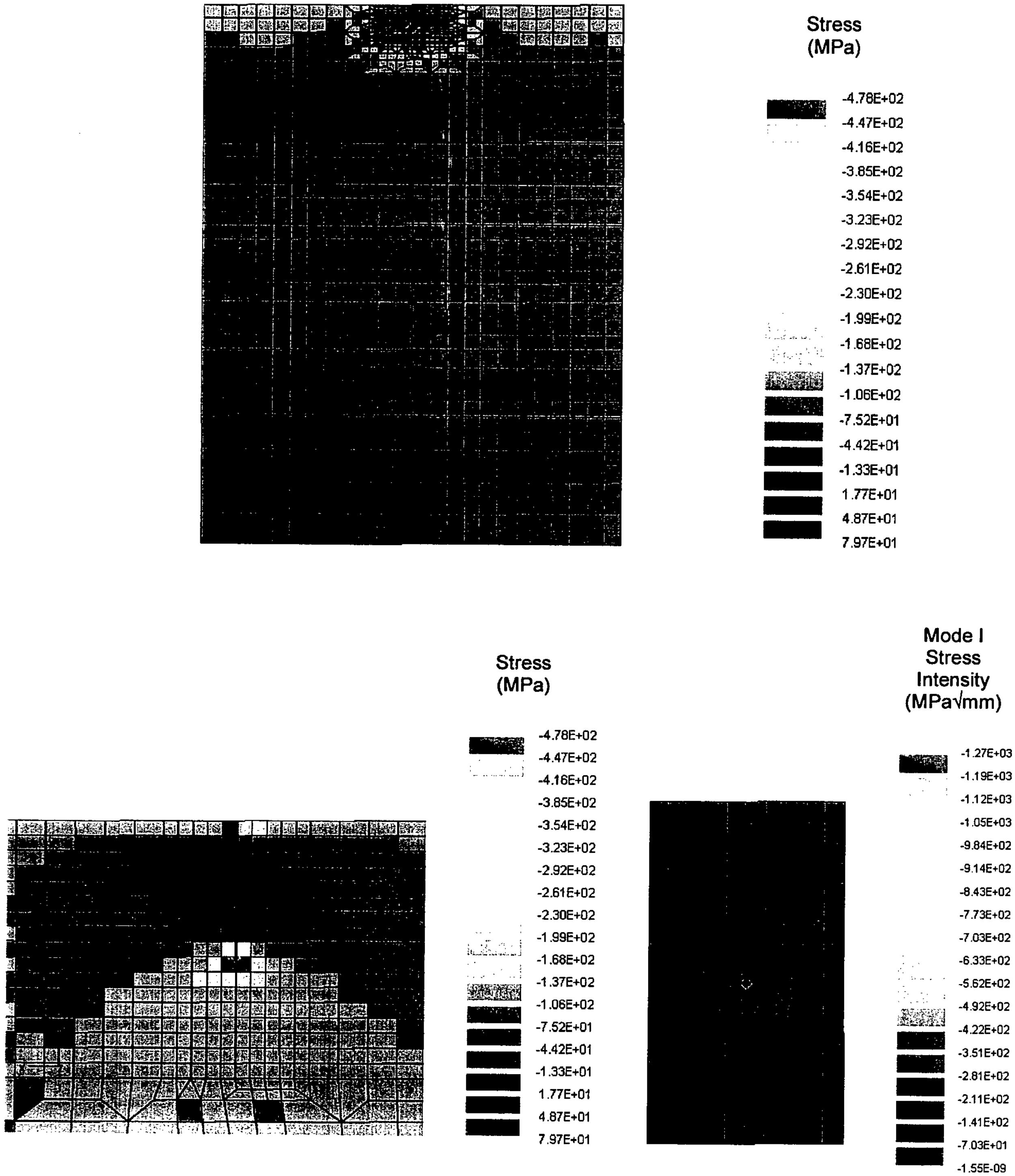


Figure 5.10: Stress Field (left) and Stress Intensities (right) for the Side Shell Model with a 100mm Crack (Case 10).

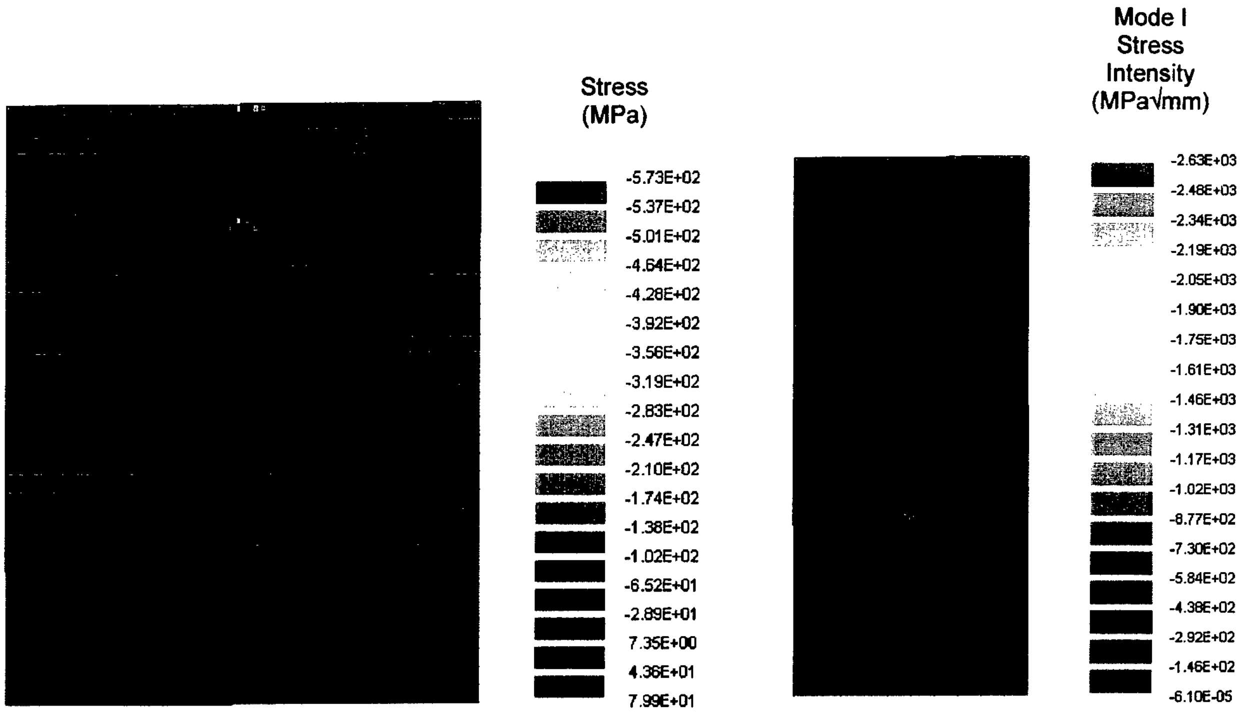


Figure 5.11: Stress Field (left) and Stress Intensities (right) for the Side Shell Model with a 500mm Crack (Case 11).

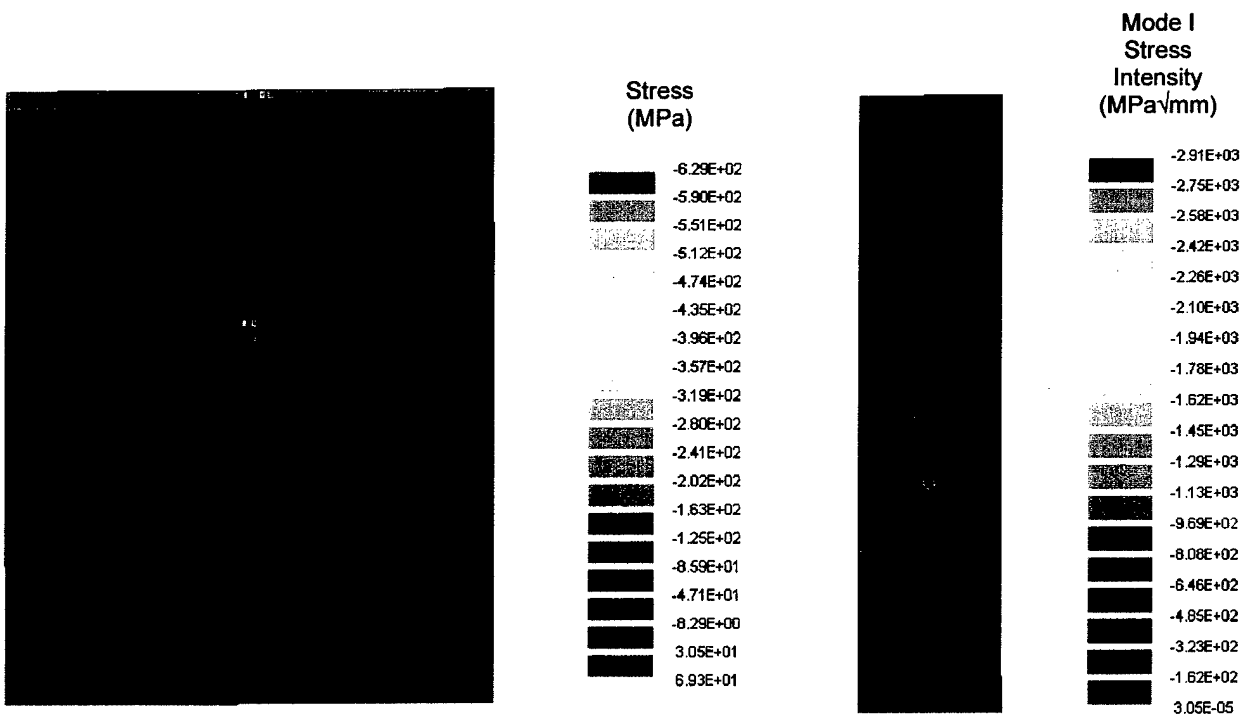


Figure 5.12: Stress Field (left) and Stress Intensities (right) for Side Shell Model with a 1000mm Crack (Case 12).

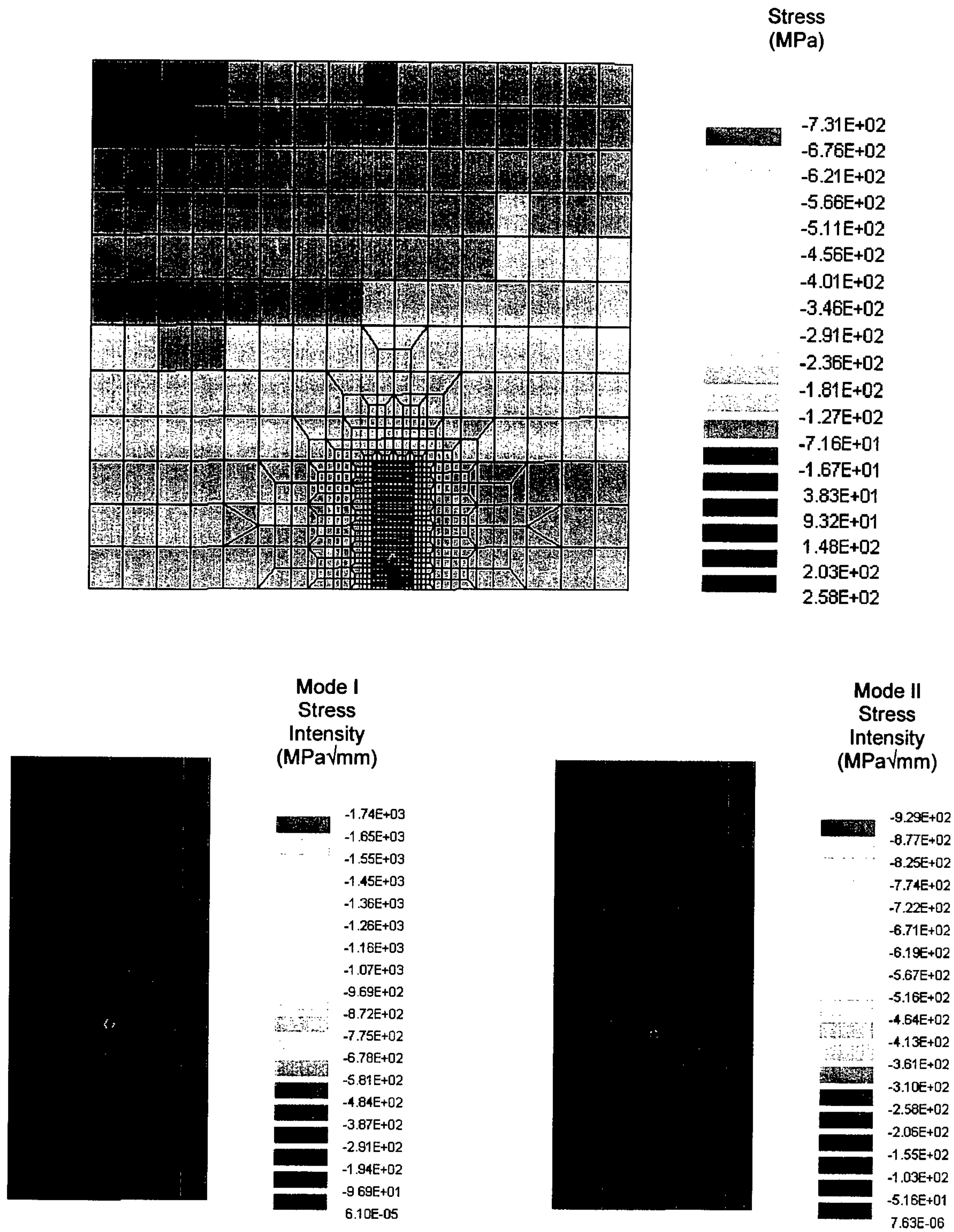


Figure 5.13: Stress Field (top) and Stress Intensities (bottom) for the Uptake Side Panel Model with a 100mm Crack (Case 13).

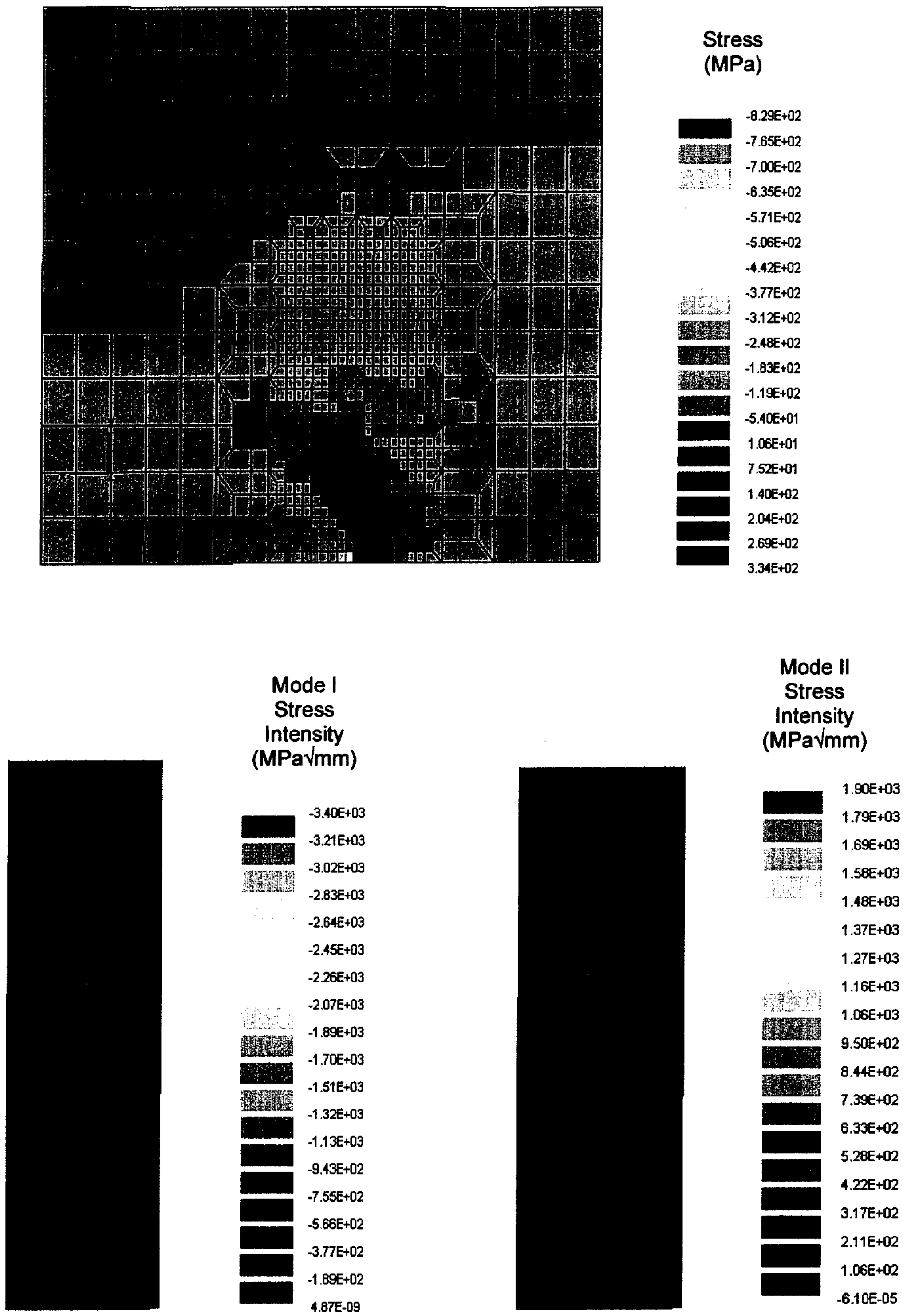


Figure 5.14: Stress Field (top) and Stress Intensities (bottom) for the Uptake Side Panel Model with a 500mm Crack (Case 14).

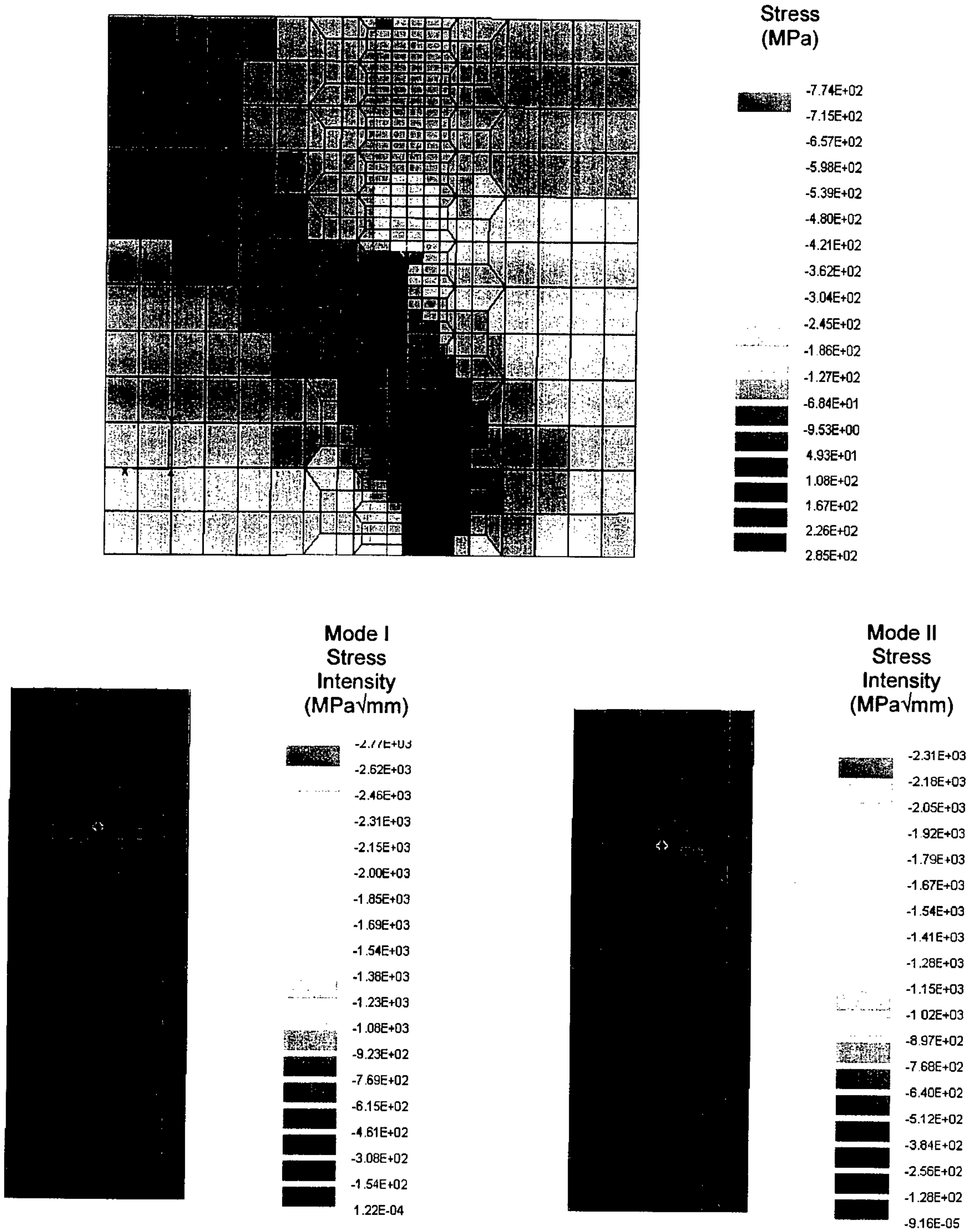


Figure 5.15: Stress Field (top) and Stress Intensities (bottom) for the Uptake Side Panel Model with a 1000mm Crack (Case 15).

6 Crack Growth Under Spectral Loading

The spectral analysis method described in Section 2.2 was used to predict crack growth for the fifteen local models. The operational profile consisted of a 100-hour voyage in head seas conditions and a significant wave height of five metres. Two ship speeds (5 knots and 16 knots) were investigated separately. Using a 200 panel model, PRECAL RAOs were obtained for thirty wave frequencies between 0.188 and 2.0 rad/s, heading angle increments of ten degrees, and both ship speeds. Unidirectional Bretschneider spectra were assumed for the wave motion. Stress intensity spectra computed with the top-down method were related to crack growth using the Paris law:

$$da/dN = C(\Delta K)^m \qquad (1)$$

where a is the crack length, N is the number of load cycles, ΔK is the stress intensity range, and C and m are experimentally determined factors. Measured values of $C = 7.40 \times 10^{-15}$ and $m = 3.49$ were used for both materials, where crack length is in millimetres and stress intensity is in MPa$\sqrt{\text{mm}}$ [11]. Only mode I stress intensity spectra were used to determine crack growth rates.

Crack growth results for initial crack lengths of 100mm, 500mm and 1000mm are shown for five crack locations in Figures 6.1 – 6.5. The average crack growth rates for each case are given in Table 6.1. These vary considerably from location to location, with the largest crack growth rate occurring in the longitudinal bulkhead (Case 8). Crack growth increases with the initial crack length in all but Cases 3, 9, and 15. For these three latter cases, the crack growth rate falls as the crack propagates into a lower stress region, with an accompanying reduction in the stress intensity spectrum.

For Case 3, some indication of this can be observed in the static stress field shown in Figure 5.3. However, the static results alone cannot explain the precipitous drop in the crack growth observed in the spectral analysis for Case 3. For this, it is necessary to compare the Case 2 and Case 3 stress intensity spectra, as shown in Figure 6.6. It can be seen that the ratio of the spectral peaks of Cases 2 and 3 is approximately 7.5. Since the Paris law (Eq. 1) is being used with $m = 3.49$, one might then expect the crack growth rates for these two cases to have a ratio of $7.5^{3.49} \approx 10^3$. This is in fact close to what is actually found in the calculated average growth rates of Table 6.1, although those values were determined from the entire spectra, not just the peak values.

The crack lengths predicted in Figures 6.1 – 6.5 are approximately linear as a function of time, indicating that the crack growth rate, Eq. (1), remains nearly constant as the crack lengthens. A notable exception is the outer main deck with an initial crack length of 1000mm (Case 6, Figure 6.2c). In this case the crack growth rate visibly drops once the crack propagates across the longitudinal stiffener located at a length of 1100 mm. The growth rate gradually increases again to its initial value as the crack approaches another longitudinal stiffener located at a length of 1650mm. A non-constant crack growth rate also occurs for the longitudinal bulkhead with an initial crack length of 500mm (Case 8, Figure 6.3b). The growth rate is clearly seen to increase at one time step

as the crack propagates from the 10mm thick section of the bulkhead to the 5mm thick section. The thickness change occurs at a crack length of 575mm.

For all cases, the growth rates at 16 knots are 2–3 times larger than the growth rates for 5 knots. This is partly due to the increase in the encounter frequency (and hence the number of load cycles), and partly due to the increase of the loading amplitude that occurs at higher ship speeds.

In four cases (Cases 2,7,11,12) the automated re-meshing step produced invalid models of the cracked component that could not be re-analysed. Evidently a fault exists in the VGCON re-meshing program which will be corrected in subsequent versions. When this occurred the iterations proceeded using the stress intensity spectra calculated for the initial crack length. Thus a constant crack growth rate is enforced throughout the remainder of the analysis, producing a perfectly linear crack length-time plot.

By themselves, the results of Table 6.1 apply to structural components for a particular sea state, heading angle, and initial crack length. More generally applicable crack growth predictions could be obtained if the results from one set of conditions could be scaled for a variety of sea states, heading angles, and initial crack lengths. This is possible because in the top-down wave loading approach, the response of the ship is assumed to be linear with the wave height. Therefore, the crack growth rate obtained for a five-metre wave height in head seas can be applied to any wave height in head seas by applying the Paris Law (Eq. 1) to linearly scaled values of ΔK. Wave height scaling factors calculated in this manner are given in Figure 6.7.

A similar scaling may be attempted for an initial crack length based on analytical expressions giving stress intensity as proportional to the square root of crack length. It has already been seen, however, that stress intensity and crack growth rate do not always increase with crack length when there is a spatial gradient in the stress field. Thus the scaling factors given in Figure 6.8, which are calculated assuming a square root law, would only be appropriate for cracks propagating in a uniform or nearly uniform stress field.

For the sake of brevity, results are given for head seas only. The same analysis could also be performed for other heading angles, for which the scaling charts in Figures 6.7 and 6.8 would also apply. In this way, a whole series of crack growth charts could be generated for every major component in the structure and for a variety of operating conditions. A comprehensive survey of this sort, however, is beyond the scope of the present study.

Table 6.1: Average Crack Growth Rates for Spectral Wave Loading in Five Metre Head Seas				
Case	Location	Crack Length (mm)	5 Knots (mm/Hr)	16 Knots (mm/Hr)
1	Inner Main Deck (A517)	100	0.0733	0.218
2	Inner Main Deck (A517)	500	0.0914	0.255
3	Inner Main Deck (A517)	1000	0.0001	0.0002
4	Outer Main Deck (350WT)	100	0.034	0.100
5	Outer Main Deck (350WT)	500	0.295	0.843
6	Outer Main Deck (350WT)	1000	1.567	5.851
7	Longitudinal Bulkhead	100	0.134	0.381
8	Longitudinal Bulkhead	500	3.581	8.553
9	Longitudinal Bulkhead	1000	2.402	6.879
10	Side Shell	100	0.046	0.188
11	Side Shell	500	1.134	3.570
12	Side Shell	1000	1.585	5.054
13	Uptake Side Panel	100	0.122	0.417
14	Uptake Side Panel	500	1.210	3.453
15	Uptake Side Panel	1000	0.632	1.625

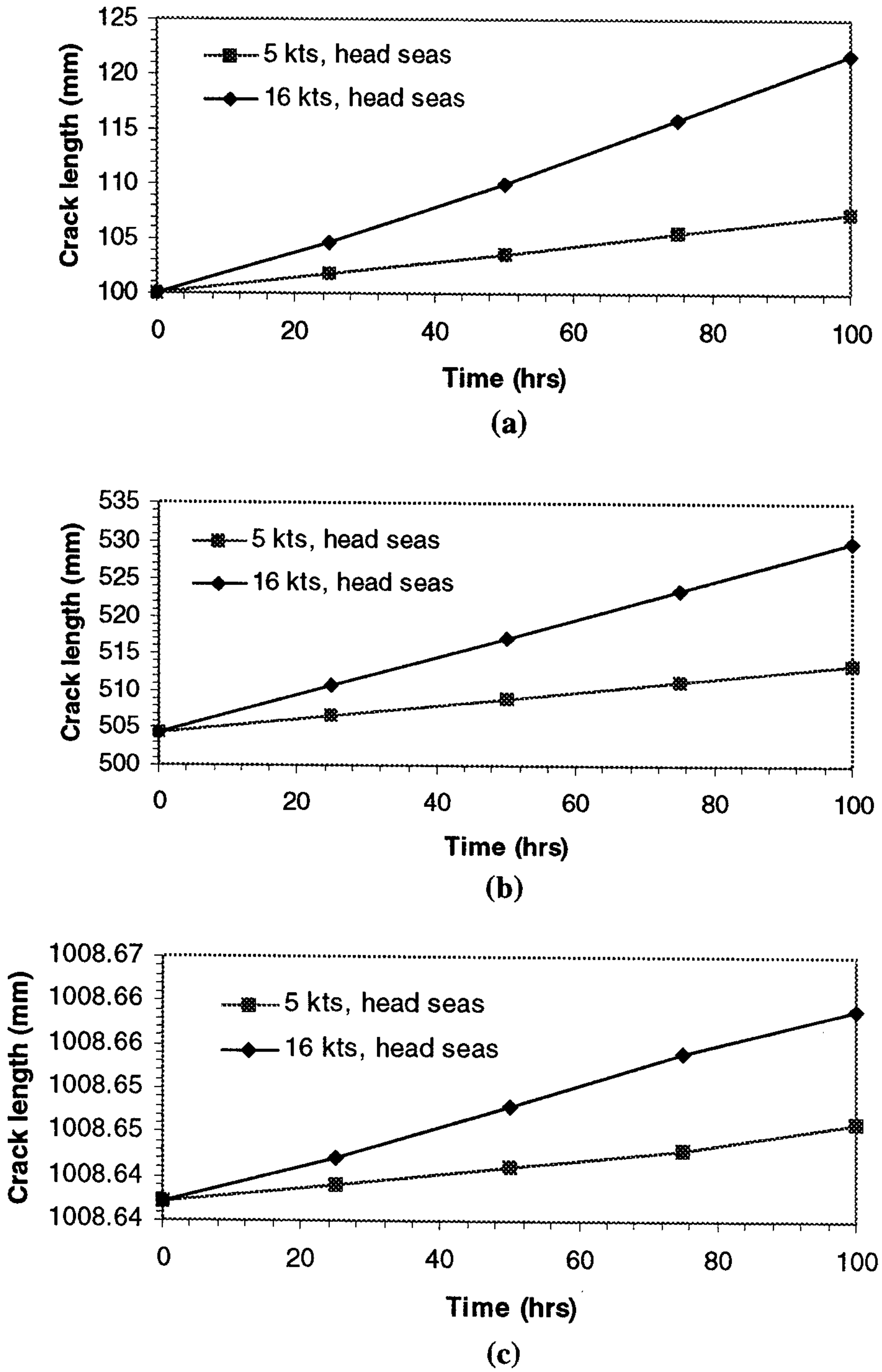


Figure 6.1: Crack Growth in the Inner Main Deck (A517 Material) for an Initial Crack Length of (a) 100mm; (b) 500mm; (c) 1000 mm.

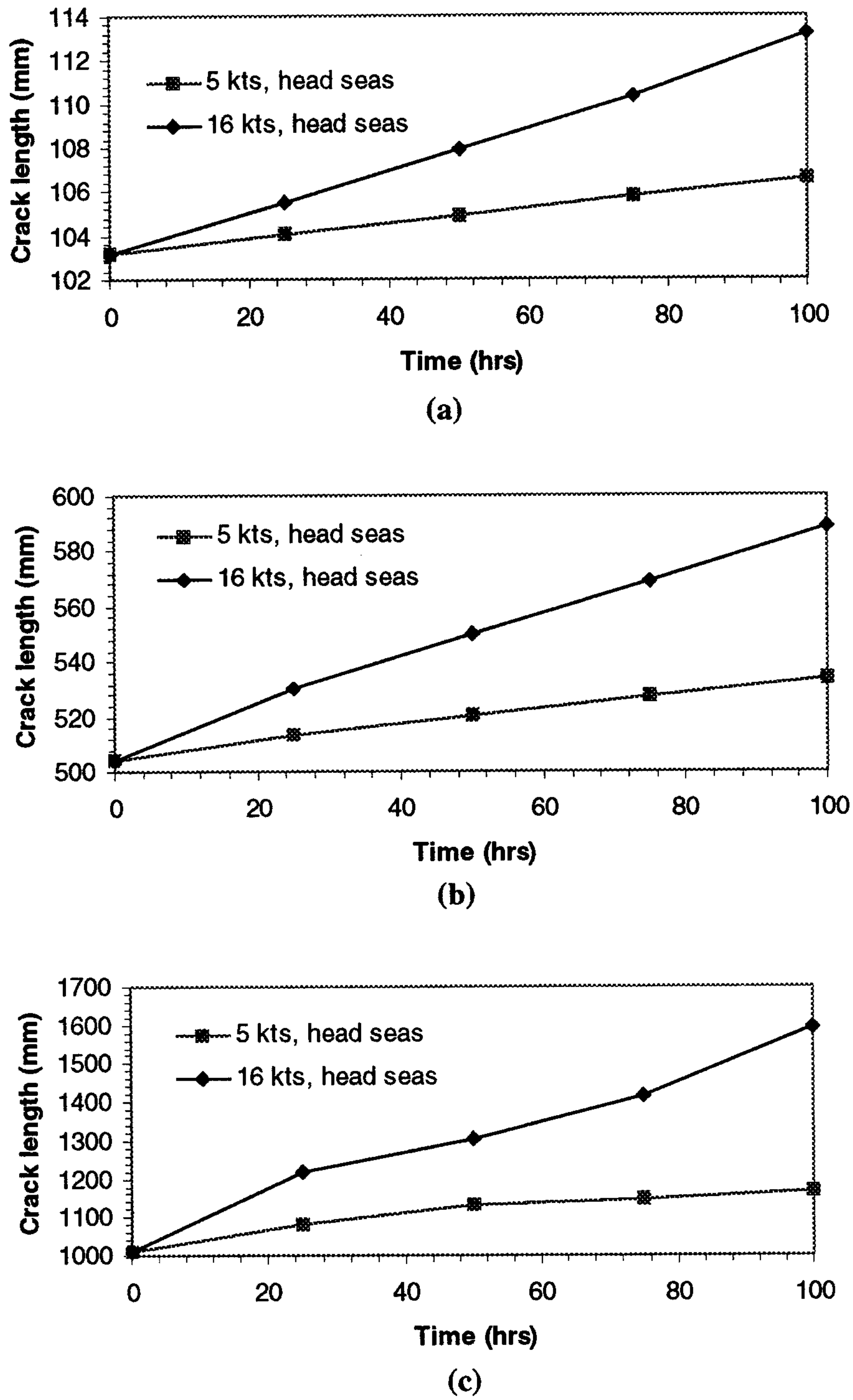
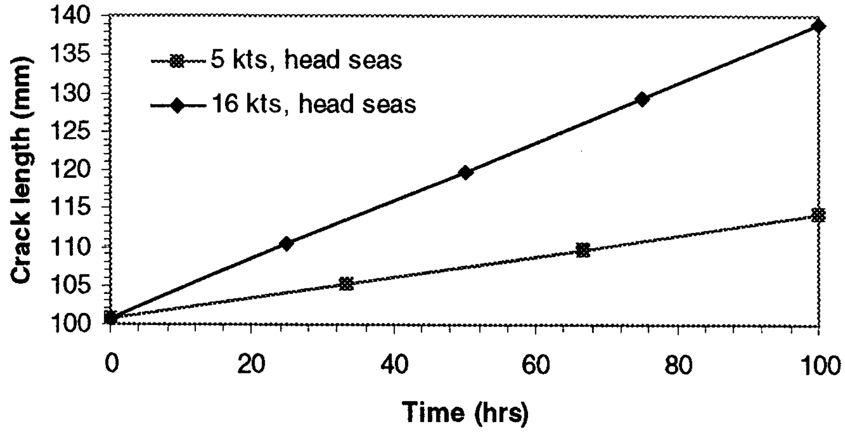
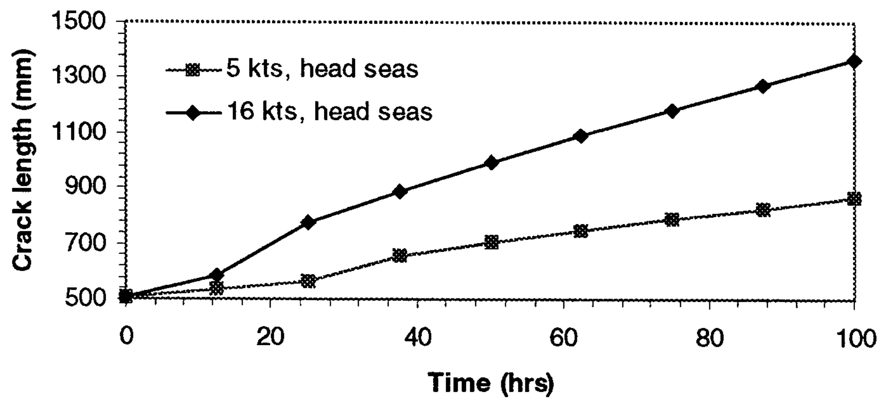


Figure 6.2: Crack Growth in the Outer Main Deck (350WT Material) for an Initial Crack Length of (a) 100mm; (b) 500mm; (c) 1000 mm.



(a)



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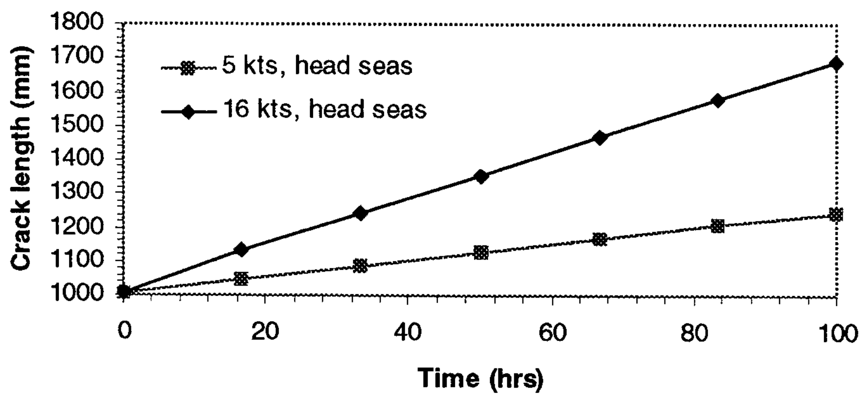

(c)

Figure 6.3: Crack Growth in the Longitudinal Bulkhead for an Initial Crack Length of (a) 100mm; (b) 500mm; (c) 1000 mm.

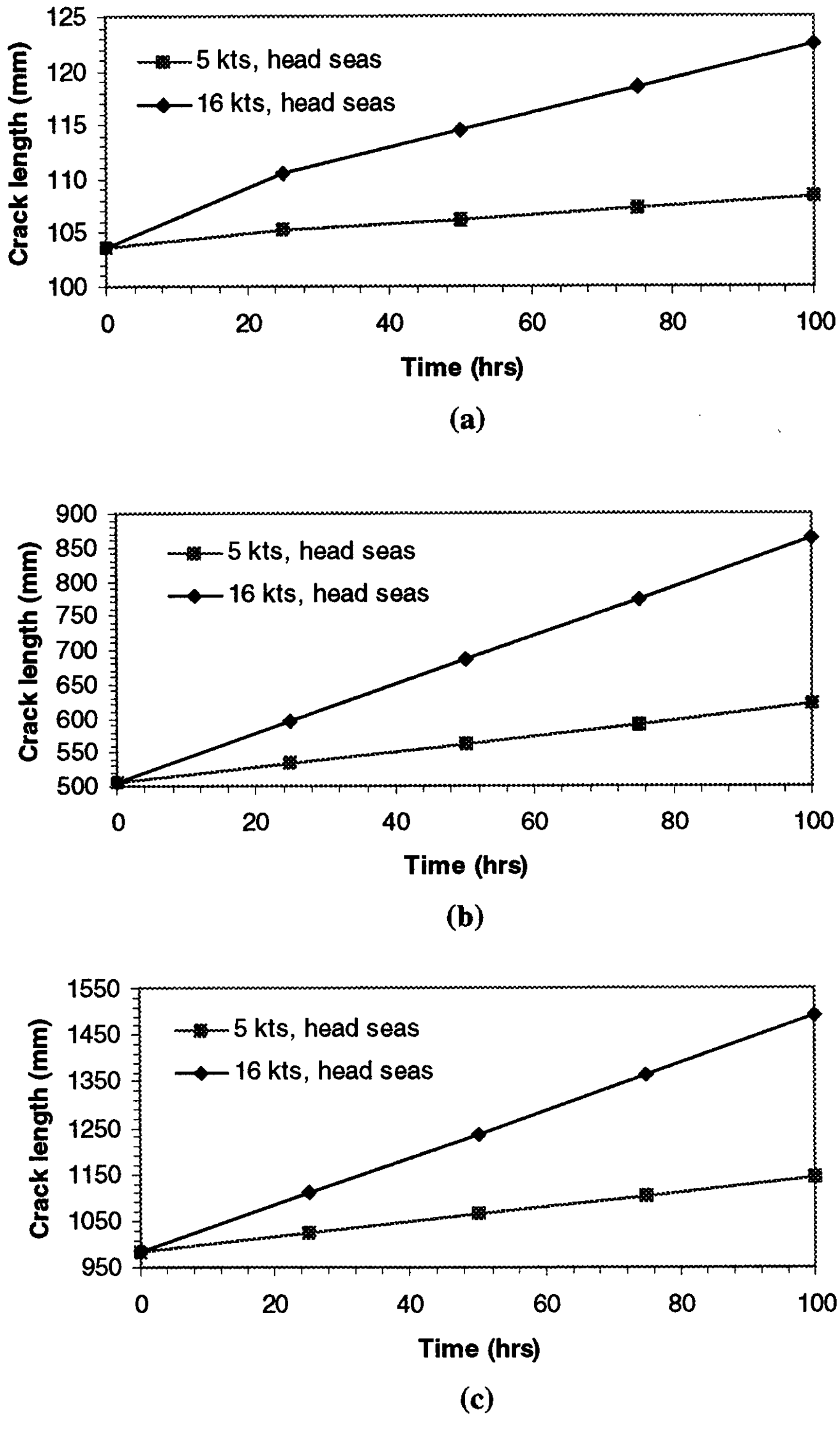

Figure 6.4: Crack Growth in the Side Shell for an Initial Crack Length of (a) 100mm; (b) 500mm; (c) 1000 mm.

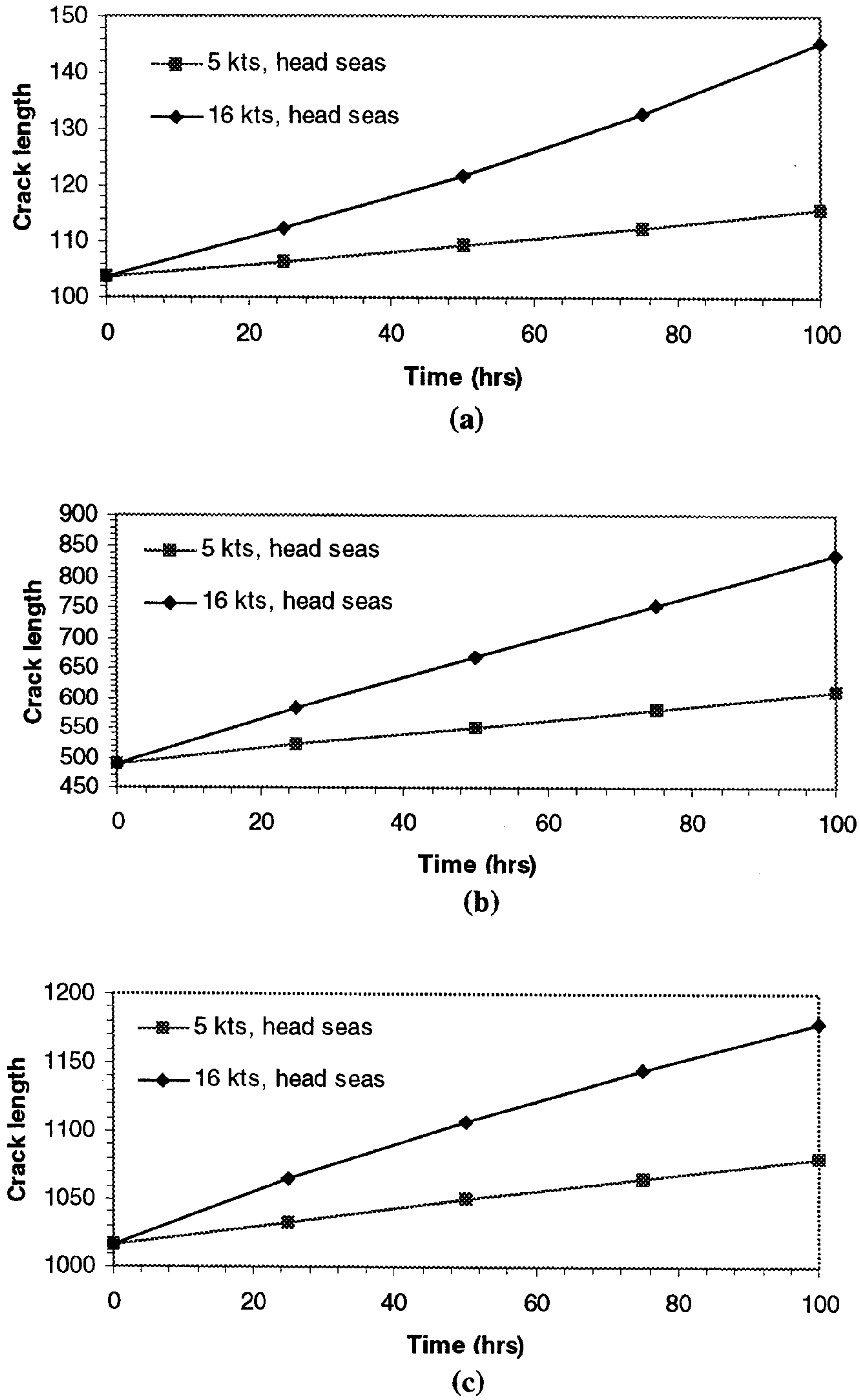

Figure 6.5: Crack Growth in the Uptake Side Panel for an Initial Crack Length of (a) 100mm; (b) 500mm; (c) 1000 mm.

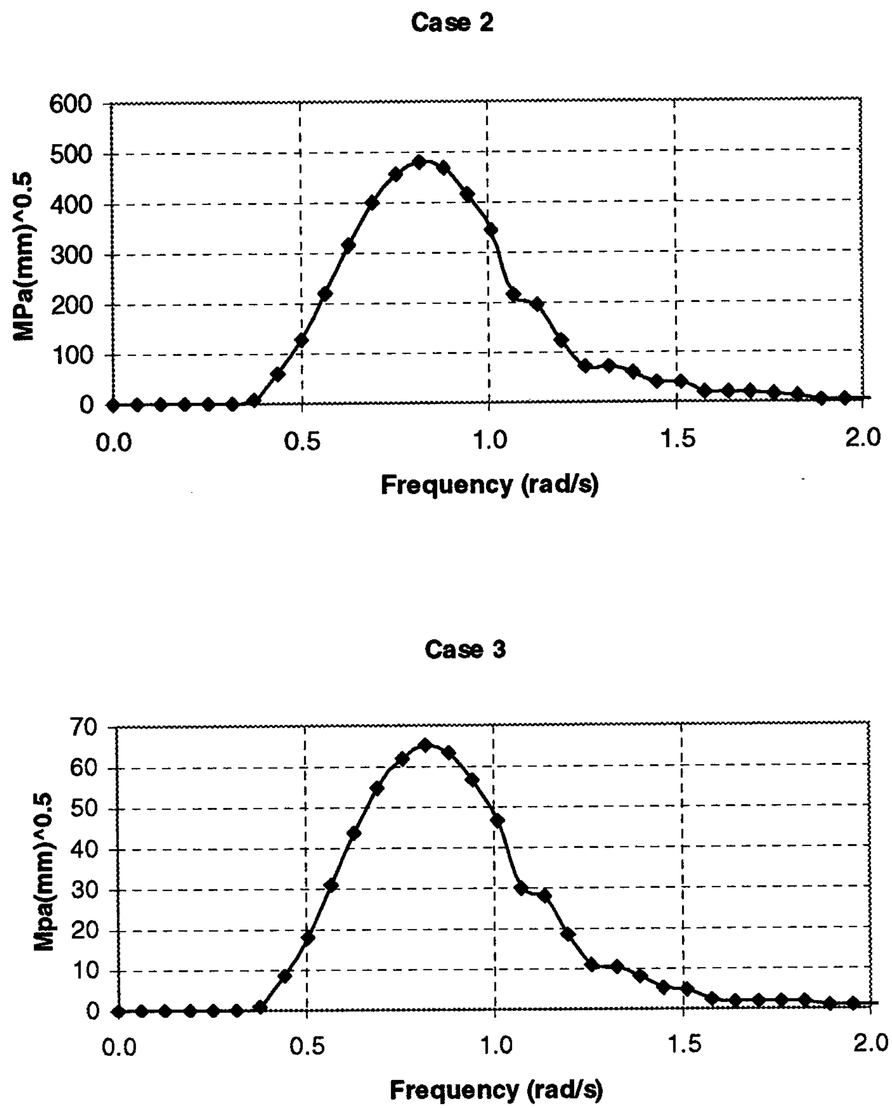

Figure 6.6: Stress Intensity Spectra calculated for a 180 Degree Heading Angle.

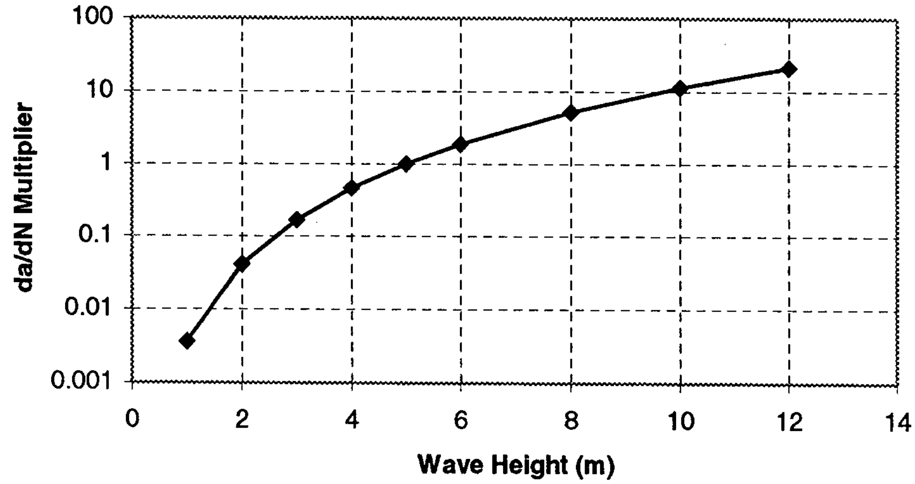

Figure 6.7: Crack Growth Scaling Factors for Values Based on Five Metre Seas.

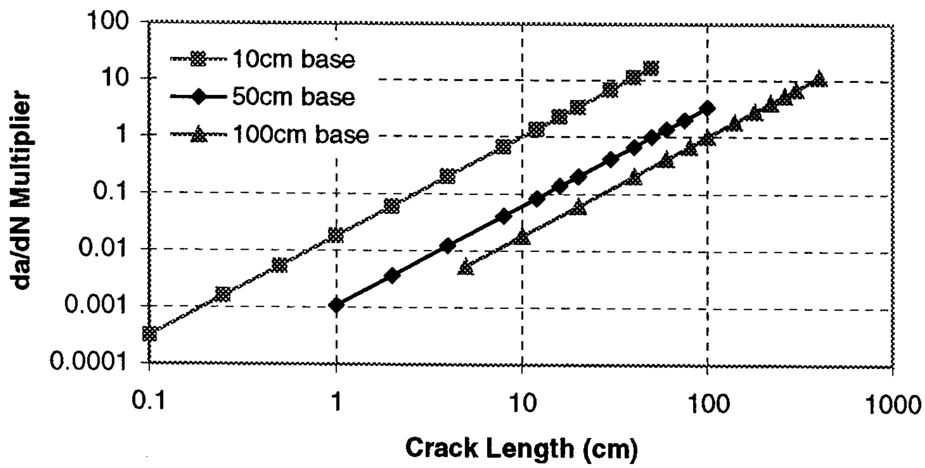

Figure 6.8: Crack Growth Scaling Factors for Values Based on Three Different Crack Lengths.

7 Conclusion

Two top-down, finite element based computational methodologies have been considered for evaluating crack growth in the Halifax class frigate. A static wave loading method was used to determine margins of safety from statically determined stress intensities, and a spectral wave loading method was used to determine crack growth rates for various locations and initial crack lengths. In all, three crack lengths at each of five locations in the high stress region of the ship have been investigated with each method.

Comparison of the static and spectral results shows that high static stress intensities under sag loading are indicative of high crack growth rates in a head seas environment. The static method, although less costly than the spectral method, does not provide time-to-failure information and is therefore mainly useful for identifying regions of high crack growth potential and suggesting failure modes. The spectral method is then needed for subsequent investigation of crack growth in given operational conditions and sea states. A combined static/spectral approach could therefore be used to perform a systematic survey of all major structural components of the ship that would provide naval personnel with sufficient data to assess the severity of any structural crack.

Some improvements in the automated re-meshing program VGCON are needed for the spectral analysis to be carried more consistently, and so that embedded smart meshes of cracks with multipoint constraints can be used in the local models. These improvements would help increase the flexibility and reliability of the software.

8 Acknowledgements

The author would like to acknowledge David Stredulinsky for providing the PRECAL results used in this study, as well as Terry MacFarlane, Alex Ritchie, and Don Smith for helping with various aspects of the modelling.

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5. DATE OF PUBLICATION (month and year of publication of document)

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The effects of artificial cracks in high stress components of the Halifax class frigate are investigated using two finite-element based methodologies currently being considered for use in the Improved Ship Structural Maintenance Management (ISSMM) project. In one method, static stress intensities are determined for each crack configuration using a one-percent exceedance wave load in sag. In the other method, the crack growth is predicted for a spectral wave loading corresponding to 100 hours in five metre head seas. A total of fifteen local models in the high stress region of the ship are investigated separately (three crack lengths for each of five locations). No evidence of uncontrolled crack growth is found using either of the two methods for any single crack configuration. The smallest margin of safety (ratio of fracture toughness to predicted stress intensity) is found to be 2.08. Crack growth rates are predicted for a 100-hour voyage in five metre head seas conditions. In this severe sea state the largest average crack growth rate is found to be 8.55 mm/hour, but at present this result has not been validated. Crack growth predictions can be extended to loadings of different magnitudes using the assumed linearity between wave height and response.

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